AN EXPERIMENTAL DEMONSTRATION OF THE BINAURAL RATIO AS A FACTOR IN AUDITORY LOCALIZATION

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TABLE OF CONTENTS

I. HISTORICAL

It is difficult to ascertain just when the belief in the binaural ratio as a factor in auditory localization came into vogue. The experimental arguments offered in favor of this belief, however, are not so hard to trace. They began with the tuning-fork experiment of Weber,[3] and have been continued

[1] *Vide* von Kries: *Ueber das Erkennen der Schallrichtung,* Zeitschr. f. Psychol. u. Physiol., I, 1890, 236-251; and Dunlap: *The Localization of Sounds,* Psychol. Rev., Monog. Suppl., Vol. X, No. 1, 1908, pp. 5, 8, 15.

[2] *Vide* Dunlap: *Op. cit.,* pp. 5, 10, and 15.

[3] Weber: Programm. Coll., 4 2. This experiment was not offered by Weber as an argument for the binaural ratio of intensity, although it has frequently been cited as furnishing such argument.

by the work of Fechner,[1] Rayleigh,[2] Politzer,[3] von Kries and Auerbach,[4] Tarchanoff,[5] Steinhauser,[6] Urbantschitsch,[7] Thompson,[8] Kessel[9] von Bezold,[10] Schaefer[11], Smith,[12] Bloch,[13] Pierce,[14] Matsumoto,[15] Melati,[16] Stenger,[17] Starch,[18] and Wilson and Myers.[19]

A résumé of this work down to 1901 has been given by Pierce It will be sufficient, therefore, for the purpose of this report to continue the résumé up to the present time, and to make a brief statement of all the lines of argument that have been advanced for the binaural ratio as a factor in auditory localization.

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[1]Fechner, G. T.: *Ueber einige Verhältnisse des binocularen Sehens* (Chap. XVIII, *Ueber einige Verhältnisse des zweiseitigen Hörens*). Abhdlg. d. Sächs. Gesellsch. d. Wiss. (Mathemat. Klasse V), Bd. V, S. 543. 1861.

[2]Rayleigh, Lord: *Our Perception of the Direction of a Source of Sound*, Trans. Mus. Ass. 1876; *Acoustical Observations*, Philos. Mag. (5) Vol. III, 1877, p. 456.

[3]Politzer: *Studien über die Paracusis Loci*, Archiv. f. Ohrenheilk. 1876, XI, 231.

[4]von Kries u. Auerbach: *Die Zeitdauer einfachster psychischer Vorgänge*, Archiv für Anatom. u. Physiol., 1877, 321-337.

[5]Tarchanoff: *Das Telephon als Anzeiger der Nerven und Muskelströme beim Menschen und den Thieren*, St. Petersburger med. Wochenschrift, 1878, No. 43, pp. 353-354.

[6]Steinhauser, Anton: *The Theory of Binaural Audition: A Contribution to the Theory of Sound*, Philos. Mag., Ser. 5, Vol. VII, 1879, pp. 261-274.

[7]Urbantschitsch, V.: *Zur Lehre von der Schallempfindung*, Pflüger's Archiv, XXIV, 1881, 579.

[8]Sylvanus Thompson: *The Pseudophone*, Philos. Mag. (5), VIII, 1879, 385-390. *On the Function of the Two Ears in the Perception of Space*, Philos. Mag. (5), XIII, 1882, 406-416.

[9]Kessel: *Ueber die Functionl der Ohrmuschel, bei den Raumwahrnehmungen*, Archiv f. Ohrenheilk. XVIII, 1882, p. 120.

[10]W. von Bezold: *Urteilstäuschung nach Beseitigung einseitiger Harthörigkeit*, Zeitschr. f. Psychol. u. Physiol., 1890, pp. 486-488.

[11]Schaefer, K. L.: *Lokalisation diotischen Wahrnehmungen*, Zeitschr. f. Psychol. u. Physiol., I, 1890, S. 300-309.

[12]Smith, G.: *How do we Detect the Direction from which Sound Comes?* Cincin. Lancet-Clinic, n. s., XXVIII. 1892, p. 542.

[13]Bloch: *Das binaurale Hören*, Wiesbaden, 1893, pp. 61; Zeitschr. f. Ohrenheilk., XXIV, 1893, pp. 25-86.

[14]Pierce, A. H.: *Studies in Space Perception*, 1901.

[15]Matsumoto: *Researches in Acoustic Space*, Studies from the Yale Psychological Laboratory, V, 1897.

[16]Melati, Gino: *Ueber binaurales Hören*, Philos. Studien, XVII (3), 1901, 431-461.

[17]Stenger: *Zur Theorie des binauralen Hörens*, Zeitschr. f. Ohrenheilk., XLVIII, 219.

[18]Starch, D.: *Perimetry of the Localization of Sound*, Psychol. Rev., Monog. Suppl. (Univ. of Iowa Studies), Vol. IV, No. 28, 1905, pp. 1-45; *ibid.*, Vol. IX, No. 2, 1908, pp. 1-55

[19]Wilson, H. A. and Myers, C. S.: *The Influence of Binaural Phase Differences in the Localizations of Sound*, The British Journal of Psychology, 1908, II, pp. 362-386.

Since 1901 reports of work on the general subject of auditory localization have been published by the following investigators: Lobsien,[1] Angell and Fite,[2] Melati,[3] Gamble,[4] Angell,[5] Seashore,[6] Bing,[7] Urbantschitsch,[8] Stenger,[9] Bard,[10] Starch,[11] Rayleigh,[12] More and Fry,[13] Bowlker,[14] Wilson and Myers,[15] and Hicks and Washburn.[16]

Of these only six bear with sufficient directness and definiteness upon the subject of this report to warrant consideration here; namely, the papers of Angell, Angell and Fite, Starch, Rayleigh, More and Fry, and Wilson and Myers.

In 1903 Angell,[17] in furtherance of the suggestions and ob-

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[1]Lobsien, Marx: *Ueber binaurales Hören und auffällige Schalllocalisation.* Zeitschr. f. Psychol. u. Physiol., XXIV, 1900, S. 285-295.

[2]Angell, J. R. and Fite, W: *The Monaural Localization of Sound,* Psychol. Rev., VIII, 1901, pp. 225-247; *Further Observations on the Monaural Localization of Sound, ibid.*, 449-459.

[3]Melati, Gino: *Op. cit.*

[4]Gamble, E. A. McC.: *The Perception of Sound Direction as a Conscious Process,* Psychol. Rev., IX, 1902, 357-373; *Intensity as a Criterion in Estimating the Distance of Sounds,* Psychol. Rev., XVI, 1909, 416-426.

[5]Angell, J. R.: *A Preliminary Study of the Significance of Partial Tones in the Localization of Sound,* Psychol. Rev., X, 1903, pp. 1-15.

[6]Seashore, C. E.: *Localization of Sound in the Median Plane,* Univ. of Iowa Studies in Psychology, 1899, 11, 46-54; *A Sound Perimeter,* Psychol. Rev., X, 1903, pp. 64-68; *The Localization of Sound,* Middletonian, 1903 (Dec.), pp. 15.

[7]Bing, A.: *Bemerkungen zur Lokalisation der Tonwahrnehmung,* Monatschr. f. Ohrenheilk., XXXVIII, 1904, 220-225.

[8]Urbantschitsch, V.: *Ueber die Lokalisation der Tonempfindungen,* Archiv. f. d. ges. Physiol. (Pflüger's), CI, 1904, 154-182.

[9]Stenger: *Op. cit.*

[10]Bard, L.: *L'orientation auditive angulaire,* Archiv. gen. de Med., CXCV, 1905, 257.

[11]Starch, D.: *Op. cit.*

[12]Rayleigh, Lord: *On our Perception of Sound Direction,* Philos. Mag., XIII, Ser. 6, 1907, pp. 214-232; *Acoustical Notes, Sensations of Right and Left from a Revolving Magnet and Telephones, ibid.*, pp. 316-319; *Acoustical Notes, Discrimination between Sounds Directly in Front and Directly Behind the Observer, ibid.*, XVI, 1908, pp. 240-241.

[13]More, L. T. and Fry, H. S.: *On the Appreciation of Phase of Sound Waves,* Philos. Mag., Ser. 6, XVII, 1907, pp. 452-459.

[14]Bowlker, T. J.: *On the Factors Serving to Determine the Direction of Sound,* Philos. Mag., Ser. 6, XV, 1908, pp. 318-332.

[15]Wilson, H. A. and Myers, C. S.: *The Influence of Binaural Phase Differences on the Localization of Sounds,* British Journal of Psychology, II, 1908, pp. 362-384.

[16]Hicks, J. and Washburn, M. F.: *A Suggestion towards a Study of the Perception of Sound Movement,* Am. Jour. of Psychol., XIX, 1908, 247-248.

[17]Angell, J. R.: *Op. cit.*

servations made by Rayleigh,[1] Thompson,[2] Mach,[3] and Pierce,[4] undertook a systematic investigation of the influence of timbre on the localization of sound. Careful observations, in the open air, were made of the accuracy of the localization of simple tones and of clangs. The sounds employed were a tuning-fork of 1,000 vibrations per second, a stopped pipe of 768 vibrations, a reed pipe of 768 vibrations, a bell with a fundamental tone of 2,048 vibrations, and the noise made by a telegraph sounder. An interpretation of his results, based on the relative accuracy of localization at different points in the vertical, horizontal, and transverse planes, led him to conclude that intensity differences alone are sufficient to enable our confident and correct assignment of the sound (even in case of pure tones) to the median plane, the lateral hemisphere, and, in a general way, to the transverse plane. But accuracy as regards altitude in the transverse plane, or in the region between the transverse plane and the median plane, is apparently dependent upon the modifications of timbre which complex sounds, coming from different directions, undergo, through changes in the intensity of their partials. Considered with reference to its bearing on the binaural ratio, the paper, in its general tone, is against the ascription of too much importance to this ratio as a factor in localization. This position is further supported by experiments conducted by Angell and Fite.[5]

The object of these experiments was to determine the localizing power of subjects who were deaf in one ear. In the first series, only one subject was experimented upon; in the second, several were used differing in age and varying in the length of their period of deafness from one to thirty years. The results of the experiments are as follows. (1) These subjects, especially when practiced, are not greatly inferior, in their power to localize, to subjects of normal hearing.[6] Dis-

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[1]Rayleigh, Lord: Transactions of the Musical Association, 1876; and Philos. Mag. (5), III, 1877, p. 456.

[2]Philos. Mag., XIII, 1882, p. 415; *ibid.* (5), VIII, 1879, pp. 385-390.

[3]Mach, E.: *Bemerkungen über die Function der Ohrmuschel*, Archiv f. Ohrenheilkunde, IX, 1875, p. 72; *Bemerkungen über den Raumsinn des Ohres*, Poggen. Annalen, CXXVI, 1865, p. 331; *Ueber einige der physiologischen Akustik angehorigen Erscheinungen*, Sitzungsberichte der Wiener Akademie, Abth. 2, L., 1864. pp. 342-363; *Zur Theorie des Gehororgans*, *ibid.*, Abth. 2, XLVIII, 1863, pp. 283-300.

[4]*Op. cit.*, pp. 92 and 163.

[5]Angell, J. R. and Fite, W.: *Op. cit.*

[6]It is assumed here that these writers would exercise caution in drawing conclusions, with regard to the relative importance of timbre and the binaural ratio of intensity in normal subjects, from the localizing power shown by subjects who have been deaf in one ear for a number of years; because the latter, deprived of the use of the binaural ratio as an aid to localization, would doubtless develop a discrimination of direction based upon difference

tinctions between front and back may be even sharper for these subjects than for those of normal hearing. The localization, however, is generally not so prompt for them as for the normal subject, nor are these subjects so accurate in dealing with unfamiliar sounds. (2) Complex sounds, especially those in which qualitative differences can be introspectively distinguished for the different positions, are localized best. The more nearly the sound approximates a simple tone, the more inaccurate is the localization. "Genuinely pure tones are essentially unlocalizable." (3) There is a marked increase in accuracy with practice. The accuracy of the practiced monaural subject, for example, was found to compare very favorably with that of the unpracticed normal subject. (4) Accuracy was also observed to sustain a close relation to the length of time the defect had existed, and to the age at which it began. For example, subjects of advanced age who had recently become deaf showed much poorer ability to localize than younger subjects who had been deaf for a number of years.

Working in 1905 and again in 1908, Starch[1] carried out an extended series of experiments on the localization of simple tones and clangs. Both monaural and binaural hearing were investigated. In the experiments with clangs, a singing flame, a Galton whistle of 10,000, 20,000, and 30,000 vibrations, the human voice, an electric hammer, a wooden clapper, and a whiff of air were used as the sources of sound. In the experiments with simple tones, a tuning-fork of 100 vibrations per second was used. In the latter experiments, tests were made at different points in the different planes of direction, (a) of the accuracy of localization, (b) of the size of the j. n. d. of direction, (c) of the limen and j. n. d. of intensity, and (d) of the j. n. d. of pitch. A number of conclusions were drawn relative to intensity and timbre as factors in localization.

Space will be taken here only for a résumé of the evidence bearing upon the binaural ratio as a factor in normal hearing, and upon intensity difference as a factor in monaural hearing. No new evidence is advanced in support of the binaural ratio, the object of the experiments apparently being a testing of the arguments already advanced by Rayleigh, Thompson,

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in timbre, considerably beyond that possessed by the normal subject. This supposition is, in fact, borne out by their own results, which show how poorly subjects recently deaf localize as compared with those in whom the defect had existed for a number of years. For example, Case F. (*Op. cit.*, p. 453), aged 60 years, deaf one year, gave correct judgments of location in only 19.5 per cent. of the total number of cases; while Case C., deaf from 26 to 30 years, gave 55 per cent. of the total number correctly.

[1]Starch, D.: *Op. cit.*

Bloch, and others. Starch finds these arguments confirmed by his own results. The arguments are: (a) the presence of front-back confusion, and its special case, the difficulty of median plane localizations; (b) the inferiority of monaural localization; and (c) the occurrence of the greatest accuracy of localization at points where slight changes in the binaural ratio are most readily perceived, *i. e.*, in front and back near the median plane, and the poorest where these changes are least readily perceived, *i. e.*, at the sides near the aural axis. Starch disagrees with Angell as to the factors in monaural localization. He maintains that, in addition to changes in the quality of a sound when it comes from different directions, there are systematic changes in intensity, which serve as a localizing clue.[1] The following evidence is given for systematic changes in intensity: (1) the limen for intensity, which is lowest in the region of the aural axis, and highest in front and back; (2) the observers' introspections with supraliminal sounds; (3) the distance tests, which showed that a sound is estimated to be nearest in the region of the aural axis. That these changes of intensive serve as a localizing clue is attested (1) by the introspection of the observers, and (2) by the poor localization when the intensity of the stimulus was varied frequently during the course of a series of experiments. The smaller j. n. d. of direction for front and back, as compared with the region near the aural axis,[2] he thinks, however, cannot be due to the intensity factor, for there is no corresponding difference in the intensity j. n. d.'s in these positions. He seems inclined to attribute this smaller j. n. d. of direction in front and back, at least in the case of his own experiments with the tuning-fork, to the qualitative factor; for his results show a smaller j. n. d. for pitch in front and back than in the region of the aural axis. Starch interprets his results as, on the whole, favoring the intensity theory. The traditional intensity theory is in the main correct; but, in order to account for monaural localization, and localization in the median plane and the planes parallel to it, this theory must be supplemented by the quality and the monaural intensity factors.

In February, 1907, Rayleigh[3] published an article in which he attempted to show that the binaural ratio cannot be a factor in the localization of sounds with a vibration fre-

[1]Starch: Psychol. Rev., Monog. Suppl., No. IV, Vol. VI, 1905, pp. 11-12; *ibid.*, No. V, Vol. IX, 1908, pp. 52-53.

[2]*Vide* Bloch: *Op. cit.*, p. 55-58; Matsumoto: *Op. cit.*, p. 65-69.

[3]Rayleigh, Lord: *On our Perception of Sound Direction*, Philos. Mag., Ser. 6, XIII, 1907, pp. 214-232.

quency of 128 per second, or less. In a previous article, published in 1876,[1] he had shown by calculations relating to the incidence of plane waves upon a rigid spherical obstacle, that a sound-wave of that vibration-frequency travelling in the line of the aural axis could not differ in intensity at the orifices of the two ears by as much as one per cent. of its total intensity. It is difficult for him to see how so small a difference could play a very important part in localization; yet he finds, at least within the limitations of his somewhat rough tests, that the tones of forks of 128 and 96 vibrations per second are localized as accurately as those of higher frequency. He infers, therefore, that there must be some other localizing clue for tones of low pitch. The only alternative to the intensity factor, he thinks, is a direct recognition of phase differences by the auditory organ.[2]

He discusses phase difference in its relation to localization as follows. When the stimulus is at one side, in the line of the aural axis, the opposite ear is "roughly about one foot" (measured on the circumference of the head) farther from the stimulus than the nearer ear. For a fork of 128 vibrations per second, this would make the phase difference between the ears about 1/8 period; for a fork of 256 vibrations, about 1/4 period; for a fork of 512 vibrations, about 1/2 period; and for a fork of 1,024 vibrations, about a whole period. "Now it is certain," he says, "that a phase relationship of 1/2 period furnishes no material for a decision that the source of sound is on the right rather than on the left, seeing that there is no difference between a retardation and an acceleration of 1/2 period. It is even more evident that a retardation of a whole period or any number of whole periods would be of no avail."

Having shown that sounds of 128 vibrations or less per second reach the ears in a difference of phase which *a priori* might be considered recognizable in sensation, Rayleigh next attempts to show that these differences actually furnish the clue for the localization of the graver tones. He works with two slowly beating tones of near 128 vibrations per second. In completing a cycle or beat, the phase differences of these tones assume all possible values. When the tones are led to the two ears simultaneously, but separately, he finds that instead of getting plainly recognizable beats, as would have occurred had both the sound-waves been given to each ear, the

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[1]Rayleigh, Lord: *Our Perception of the Direction of a Source of Sound.* Transactions of the Musical Association, 1876.

[2]The sound wave coming directly to both ears from a single source could show differences only in complexity, intensity, and phase. The first of these differences is ruled out of consideration by the use of the tuning-fork; the second, by his mathematical calculations.

whole sound mass seems to be transferred alternately from one side to the other. In order to interpret these results, he conducted a second series of experiments. The following results were obtained. (1) It was shown that the transference of the sound from one side to the other came directly after ("followed") the maxima and minima of sound as heard by a second observer, for whom the beats were allowed to occur. This established a correlation between the maximal changes in phase of the sound-waves received by the two ears and the phenomenon of transfer. (2) It was found, in addition, that when the wave of greater frequency was received by the right ear, for instance, the transfer to right occurred directly after agreement of phase, and the transfer to left came directly after the maximal opposition of phase. "The transitions between right and left effects correspond to agreement and opposition of phase, not usually recognized. When the vibration on the right is the quicker, the sensation of right follows agreement of phase, and (what is better observed) the sensation of left follows opposition of phase." The writer interprets this quotation to mean that the sound is heard on the right from agreement to opposition of phase, and on the left from opposition to agreement. Now a consideration of the phase relationships of two sound-waves differing in frequency shows that the wave of greater frequency leads in phase from agreement to opposition, and the wave of lesser frequency leads from opposition to agreement.[1]

[1]The writer can best show in the following manner what he conceives Rayleigh to mean by leading in phase. The vibrating particles forming each sound-wave execute simple harmonic motion. They may thus, in each case, be considered as moving on the circumference of a circle whose diameter is equal to the amplitude of vibration. For the sake of ready comparison, their amplitudes of vibration may be assumed as equal; and both may be considered as moving on the circumference of the same circle,

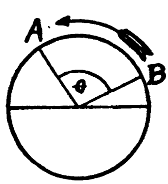

FIG. 1

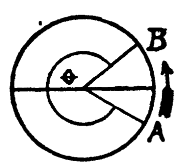

FIG. 2

but at different rates of speed. Taking any two corresponding particles of the two waves, he considers that when the angle θ (the angle separating the radii at the outer termini of which the two moving particles are located, measured in the direction in which the particles are moving) is less than 180°, the particle moving at the greater rate of speed, considered with reference to the direction in which both are moving, will be ahead of the

Thus it can be inferred that the sound was referred throughout in these experiments to the side receiving the wave leading in phase. Rayleigh proposes to make of this a localizing clue, and applies it as a principle of explanation to the phenomenon of localization, as ordinarily observed, for all tones of low pitch. For example, when the source of sound is situated to the right or left of the median plane, the sensation is referred to the right or left, as the case may be, because at any given instant the wave acting upon the ear in question leads in phase the wave acting upon the other ear. And when the source is in the median plane, the sound is referred to that plane because the wave reaches the two ears in phase agreement. Continuing his experiments with forks of higher pitch, Rayleigh finds that the right and left effects occur without considerable diminution up to pitches of 320 vibrations per second. At this point the phenomenon begins to become indefinite and confused. After careful variations of his conditions, he concludes that 768 vibrations per second furnish the limit beyond which no trace of the effect is observed.

In a later report of work,[1] Rayleigh says: "When the sounds proceed from tuning-forks vibrating independently, the phase differences pass cyclically through all degrees, and if the beat be slow enough there is good opportunity for observation. But it is not possible to stop anywhere, or in some uses of the method to bring into juxtaposition phase relationships which differ finitely." He then describes a method of experimentation which allows any particular phase relation to be maintained at pleasure. Two telephone receivers were used as sources of sound. They were excited by a revolving magnet which acted indirectly upon two coils, one in each of the telephone circuits. The planes of the coils were vertical, their centres being at the same level as the magnet. One was fixed, and the other was so mounted that it could revolve about an axis coincident with that of the magnet. The angle between the

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slower particle; and, conversely, when the angle θ is greater than 180°, the faster particle will always be behind the slower particle. To illustrate (Fig. 1), let A represent the position of the faster particle on the circle of reference and B the position of the slower particle, both moving in a counter-clock-wise direction. When angle θ is less than 180°, A will be ahead of B; but when angle θ is greater than 180° (Fig. 2), B will be ahead of A. When angle θ is 180°, or 360°, neither will lead in phase.

The phase relations which any two particles vibrating at different rates will sustain at different times can be very prettily shown for class demonstration by two hands geared to move at the required speeds around a graduated dial.

[1] Lord Rayleigh: *Acoustical Notes, Sensations of Right and Left from a Revolving Magnet and Telephone*, Philos. Mag., Ser. 6, XIII, 1907, pp. 316-319.

planes of the coils represents the phase differences of the periodic electro-motive forces, subject it may be to an ambiguity of half a period, dependent upon the way the connections are made. If the circuits are similar, as is believed, the phase differences of the circuits and the electro-motive forces are the same. The circuit of one telephone included a commutator by means of which the current through the instrument could be reversed, corresponding to a phase change of 180°.

In conducting an observation, the sounds given by the two telephones are brought to equal intensities by a proper regulation of the distances between the magnets and the inductor coils. The telephones are thus brought into simultaneous action, and differences of phase are produced by rotating the movable coil; or if complete reversal is wanted, it may be got by means of the commutator. The results, he says, confirm those obtained with the tuning forks. A lead in phase was followed by the reference of the sound to the side receiving the wave which led in phase, and when the planes of the coils were parallel, *i. e.*, when the phases were in agreement or opposition, the sound was located in the median plane.

It may be of interest to note here the results of other observations made under conditions similar to those obtaining in Rayleigh's experiments. Thompson, working in the following way, reports beats, but makes no mention of right and left effects. (1) Tuning-forks, unresonated, were held one to each ear. (2) The sound of one fork was conducted to one ear through a rubber tube and the second fork was held to the other ear. (3) The forks were placed in different rooms and the sound was conducted separately through rubber tubes to the ears. The sounds had no opportunity of mingling externally or of acting jointly on any portion of the air columns along which the sound travelled. Speaking of this observation, he says (Philos. Mag., Ser. 5, III, 1877, p. 274): "The beats were most distinctly heard, and seemed to take place within the cerebellum." So W. H. Stone reports (*Ibid.*, p. 278) that he has been in the habit of using both ears, with a tuning-fork applied to each, in counting beats; and that he finds no difference between the results of this method and that of listening to both forks with one ear. Rayleigh (*On our Perception of Sound Direction*, Philos. Mag., Ser. 6, XIII, 1907, p. 220), speaking of Thompson's results, says: "In an observation of my own (Philos. Mag., Vol. II, 1901, p. 280; Scientific Papers, Vol. IV, p. 553), when tones supposed to be moderately pure were led to the ears by means of telephones, a nearly identical conclusion was reached. But although the cycle was recognized, in neither case, apparently, was there any suggestion of right and left effect. In repeating the experiments recently, I was desirous of avoiding the use of telephones or tubes in contact with the ears, under which artificial conditions an instinctive judgment would perhaps be disturbed. It seemed that it might suffice to lead the sounds through tubes whose open ends were merely in close proximity one to each ear, an arrangement which has the advantage of allowing the relative intensities to be controlled by a slight lateral displacement of the head toward one or the other source." This apparently was the only difference in the conditions between the experiments which gave beats and no right and left effects, and the experiments which gave right and left effects but not "plainly recognizable beats." Hermann (*Zur Theorie der Combinationstöne*, Pflüger's Archiv, XLIX,

1891, pp. 499-518) found that when the waves from two tuning forks were conducted one to each ear, he heard both beats and combination tones. In this case he supposed that the tones, through the mediation of the bones in the head, both acted together on each ear. No mention is made of right and left effects. Cross and Goodwin (Charles R. Cross and H. M. Goodwin: *Some Considerations Regarding Helmholtz's Theory of Consonance*, Proc. of the Am. Acad. of Arts and Sciences, XXVII, 1891, pp. 1-12) found beats and apparently the phenomenon of transfer from ear to ear. The meatus was closed with beeswax, leaving an air column between it and the tympanic membrane. The conduction under these conditions they think was directly to the tympanic membrane by means of the air column and not through the bones of the head to the middle ear or cochlea, because the sound of the fork, when the stem was touched to the wax, was heard long after it had ceased to be audible when the stem was touched to the pinna of the ear. It was also found that it could be heard longer when the stem was touched to the wax than when it was held against the teeth. When two small tonometer forks, tuned to four beats per second, were struck and their stems held against the teeth, "loud beats were heard in the ears. . . . . . The forks were held in this position until the beats had entirely ceased to be audible, when they were removed and the stem of each was touched to the wax closing the two ears. Instantly the two notes were heard, faintly but distinctly, in the ears to which they were held, and accompanying them were faint beats seeming to wander in the head from ear to ear, as is always the case with binaural beats." The experiment was then varied slightly as follows. One ear only was closed with wax; the other was immersed in a large basin of water. "The experiment was then repeated as above, with the difference that one fork, instead of being touched to the ear, was touched to the marble basin, its vibrations being transmitted to the enclosed ear through the water. The same results were obtained as before." One of the conclusions drawn from these experiments, which is especially of interest relative to Wilson and Myers' experiments and their explanation of the localization of tones of low pitch (*Vide* this paper, pp .266-69), is that "aerial vibrations acting upon the ear are not transmitted through the skull, or bony parts of the head, from one ear to the other."

The phenomenon of beats has also been reported in this connection by the following experimenters, but none of them has mentioned a right-left transfer: Dove (Repertorium der Physik, Bd. III, 1839, S. 494; Pogg. Annal., CVII, 1859, S. 653); Seebeck (Pogg. Annal., LIX, 1841, S. 417; *ibid.*, LXVIII, 1846, S. 449; Akustik, Abschn. II, Gehler's Repertorium der Physik, 1849, S. 107); Mach (Wiener Sitzungsber, L, 1864, p. 356.); Stumpf (Tonpsychologie, Bd. II, S. 208, 458, 470); Bernstein (Pflüger's Archiv., LIX, S. 475); Ewald (Pflüger's Archiv, LVII, 1894, S. 80); Schaefer (Zeitschr. f. Psychol., u. Physiol., I, 1890, 81); and Melati (Philos. Studien, Bd. XVII, 1901, pp. 431-461). Sanford (Experimental Psychology, 1898, p. 82), however, working with forks beating once in two or three seconds notices, a shifting of the sound from ear to ear corresponding to the rate of beating.

It is with considerable reluctance that the writers present the preceding brief exposition of Rayleigh's theory and its experimental confirmation, because neither of these is worked out in the original article with sufficient detail to warrant the risk of a definite interpretation. In every case, therefore, where more than one interpretation has seemed possible, the one most favorable to the theory has been chosen. Until all the points involved both in the theory and in its confirmation have received more definite treatment by Rayleigh

the writers feel that positive criticism, either favorable or adverse, is out of the question. The following comments, however, may not be out of order. (1) The theory is purely physical. No attempt is made in any of the points to bridge over the gap between stimulus and sensation. In the treatment of lead and lag, for example, no consideration is given to what the ear, as a sense-organ, might be assumed to recognize as lead and lag. The mathematical propriety of Rayleigh's use of the terms is granted. And by mathematical definition, the faster wave will lead when angle θ is less than 180°. There will always be this characteristic phase relation between the waves coming to the two ears. But to grant that the ear can discriminate which is leading and which lagging, when no position or motion of any of the vibrating parts of the ear can, in the complete cycles of its changes, characteristically stand for lead or lag, and when no lead and lag aspect can be discovered in the sound sensation itself, seems to be ascribing to the auditory mechanism a logical or mathematical power which not even all educated beings possess as an item of culture. For example, when angle θ is say 160°, the faster wave may, at different times when this angle of separation occurs, be in every conceivable stage either of condensation or of rarefaction. During a part of this time, the slower wave will be at appropriate points in rarefaction when the faster is in condensation, and *vice versa;* and the rest of the time both waves will be either in rarefaction or condensation. Thus there is nothing in the position or motion of the vibrating structures of the ear that can be seized upon as characteristic of the lead or lag, as Rayleigh uses the terms, except a relation between direction of motion and angles of separation, and this is discovered only by a mathematical consideration of simple harmonic motion.[1] Just as Helmholtz's theory of vision has

[1]There is, for example, an alternative interpretation of lead and lag, which, it seems to the writers, the ear might more plausibly be assumed to recognize; namely, neither particle might be said to lead or lag unless both be moving either in condensation or rarefaction. Then the vibrating structures of the ear will be moving in the same direction, and at any given moment will be displaced in the same direction. Thus, as far as sensations of motion or position are concerned, if such sensations can be assumed for any of the vibrating structures of the ear, there would be a better chance for comparison than by the former interpretation. The writers, however, do not consider that this is the interpretation Rayleigh means to be taken for lead and lag; because (1) it is not the interpretation commonly given to the terms, and (2) in his experiments, it would leave the ear a part of the time in both halves of the cycle of changes without a localizing clue, for there will come times both from agreement to opposition and from opposition to agreement when one wave will be in condensation and the other in rarefaction, and conversely. Thus for a part of the time, in both cases of reference, right and left, there would be no localizing clue. This interpretation would

been called pre-psychological, so may this theory of localization be called pre-psychological.

(2) Speaking of the difference in phase inwhich the sound-wave from a source to the right on the aural axis would arrive at the orifices of the two ears, Rayleigh says:[1] "It is easy to see that the retardation of distance at the left ear is of the order of the semicircumference of the head, say one foot. At this rate, the retardation for middle C ($C'=256$) is nearly one quarter of a period; for C'' (512) nearly half a period; for C''' (1024) nearly a whole period, and so on. Now it is certain that a phase retardation of half a period affords no material for a decision that the source is on the right rather than on the left, seeing that there is no difference between a retardation and an acceleration of half a period. It is even more evident that a retardation of a whole period or of any number of whole periods would be of no avail." In the preceding quotation just two stages of phase relationship are ruled out as furnishing no localizing clue; namely, a difference of a half period, and a difference of a whole period. A difference of a half period furnishes no clue, because the angular separation of corresponding particles of the two waves is 180°; hence it would be the same whether considered as acceleration or retardation. Similarly, a difference of a whole period furnishes no clue, because the angular separation of the corresponding particles of the two waves is 360°, hence would be the same considered either as acceleration or retardation. But in the scale of pitches, there are only certain members higher than 512 and 1,024 vibrations whose sound-waves coming from a given direction would always arrive at the two ears with a difference of 180° or 360°. Phase difference, so far as can be readily seen, should furnish a clue for the localization of the higher just as well as of the lower pitches. There seems to be no good reason, then, for making the direct recognition of phase difference a localizing clue for the lower pitches only, and for giving over to difference of intensity the exclusive rôle for the higher pitches. And again, if a direct recognition of phase difference be a localizing clue, it is not easy to see why the right and left effects in Rayleigh's experiments should suffer considerable diminution when the tones were as high as 320, and should cease entirely near 768 or above. It is just as clear that the faster wave will lead from agreement to opposition and the slower from opposition to agreement in this case as in the case of lower tones. And if the tones

work even worse in localization as ordinarily observed, for in every direction there would be certain distances from the ear for which there would be no localizing clue.

[1] *Op. cit.* p. 218.

were near together in pitch, the transitions from right to left effects should have come just as slowly and should therefore have been just as easily observed. That is, if 768 and 769 forks were used, for example, the change from agreement to opposition and from opposition to agreement, and the corresponding right-left, left-right transfers, should have occurred only once per second, just as would have occurred with forks of 128 and 129 vibrations per second. (3) Phase difference must make itself felt in consciousness either by means of some change in the sound sensation itself, or by setting up some new sensation alongside the sound sensation; for example, a sensation of position or movement of some of the vibrating structures of the ear. Wilson and Myers[1] conclude that phase difference makes itself felt as a difference in the intensity of the sound heard by the two ears. They explain the localizations in Rayleigh's experiments in terms of this difference in intensity produced by cyclic changes of interference between the sound-waves coming directly to the two ears and those transmitted from one ear to the other through the bones of the head. Rayleigh, however, obviously considers that the effect of phase difference is extra to any differences that may occur in the intensity aspect of the sensations given to the two ears. The question arises as to whether either explanation can be applied further than to the special phenomenon created by the experimental conditions under which they worked. This point will be taken up in a later section of this paper. (4) Until more sensitive tests than those conducted by Rayleigh are made to find out the relative sensitivity of direction-discrimination for low and high tones, it is not demonstrated that there is any need for a supplement to the intensity theory, to account for the localization of low tones.

Later, in 1907, More and Fry[2] also attempted to show that phase difference serves as a clue for the localization of sound. They worked with tuning-forks of 320 and 512 vibrations per second. The observer was seated at the centre of a large circle marked on the floor of a room. The zero point in the circle was taken directly behind the observer, the 180° point in front, and the 90° points at the sides. A glass funnel 13.5 cm. in diameter was mounted horizontally on a table at the zero point, about 7 ft. behind the observer. Heavy rubber tubing with an inner diameter of about 1.2 cm. connected the funnel with the stem of a glass Y-tube, on the two branches of which rubber tubing of the same size was fitted. These branch tubes ended in glass tubes bent so as to fit into the ears of the ob-

[1] *Vide* pp. 267-68, this paper.
[2] *Op. cit.*

server. Each of the branch tubes was cut in two at the middle; and by inserting pieces of glass tubing, the experimenter readily altered their lengths without the listener's being aware of the change. Fourteen observers were used. The sound was given at the mouth of the funnel, and the observer was asked to indicate the direction from which it came. This direction was estimated by means of the graduated circle at the centre of which the observer sat. Before each observation, the length of one of the tubes was changed 1/8, 1/4, 3/8, 1/2, 5/8, 3/4, or 7/8 of a wave-length of the sound used as stimulus. The results, expressed in general terms, showed that when the tubes were exactly equal in length, the sound seemed to come directly from behind; but if one tube was made shorter than the other, by as much as 2 cm., the sound was referred to the side having the shorter tube. These results were taken to indicate that sound is localized by a direct appreciation of the difference of phase of the waves coming to the two ears.

With regard to this work, the writer would point out the following facts. (1) The forks employed were both above the pitch limit at which Rayleigh claims the difference in intensity becomes too small to serve as a localizing clue. Hence these writers, in their support of the phase difference theory, work with tones for which Rayleigh claims the localizing clue is difference of intensity and not of phase. (2) Their results, stated in general terms, do not seem to have any differential value. When one tube is made shorter than the other, the stimulus received by the ear on that side is more intensive than that received by the other ear; hence, by the intensity theory, as well as by the phase difference theory, the sound should be referred to that side. The sounds worked with had a wave-length of 64 (512 fork) and 104 (320 fork) cm. per sec. A change in the length of one of these comparatively short tubes by from 1/8 - 7/8 of a wave-length of these sounds would produce a considerable change in the ratio of the distances the sound had to travel to reach the two ears; hence it would produce a considerable difference in the energy of the stimulation given. As nearly as the writer can determine, by comparing the measurements and localizations given by More and Fry with the measurements of the direct paths of transmission of the sound to the two ears from these locations in his own sound-cage, the change of ratio is quite of the same order in the two cases.

(3) Although it may be considered that the results in general are not differential as between the two theories, More and Fry find a crucial argument in the fact that as one tube was progressively made longer than the other, there was not a constant increase in the displacement of the sound toward the ear sup-

plied with the shorter tube. In a few cases, for example, the 90° displacement was made when the change in the length of the tube was only 5/8-3/4 of the wave-length; and from that point on to a change of a whole wave-length, there was even, in certain cases, a decrease in the angle of displacement. This, they say, on the basis of the intensity theory, ought not to be. There should be, following a change in the relative lengths of the tubes, a regular increase of displacement. To quote: "If it were a question of change of intensity, the change in direction would increase continually and not reach an angle where further increase in the length of the tube produces either a doubtful increase in angle or even at times a decrease." In reply to this, it may be pointed out (*a*) that a sound cannot be displaced more than 90° to either side, and the ratio of the length of the tubes which gave their observers a displacement of the sound 90° to the right was of the same order as the ratio of the lengths of the direct paths of transmission to the two ears when the sound is actually given 90° to the right in the sound-cage used in our own experiments. Moreover, as localizations ordinarily occur in everyday life, the ratio of the distances the sound travels in order to reach the two ears is, in most cases, not even so great as it is with the Titchener sound-cage. The above result, then, is all that could be expected by the intensity theory. (*b*) To account for the decrease in the angle of displacement in a few cases mentioned, it may be said that when the ratio of intensity, by the conditions of the experiment, is made to exceed any ratio that could occur in our daily life, there is no basis for the association of any given direction with that ratio; hence, once this limit is exceeded, regularity of results should not be expected. Under such conditions, one might expect almost any irregularity, but certainly not regularity.

(4) The discrepancy between More and Fry's and Wilson and Myers's[1] results should not be ignored. In both cases apparently the same method of working was used, yet very different results were obtained. For More and Fry's observers a change in the relative lengths of the tubes was followed uniformly by a displacement of the sound toward the side of the shorter tube; while for Wilson and Myers's observers, changes in the length of the tubes were followed by a cycle of changes of localization,—first to the side of the shorter tube, then to the median plane, to the side of the longer tube, back to the median plane, and so on. So great a discrepancy cannot but throw both sets of results open to question, until more work is done under similar conditions.

[1] *Vide* this paper, pp. 266-67.

In October, 1908, Wilson and Myers reported a series of experiments suggested by the work of Rayleigh. The general plan of experimentation was similar to that used by More and Fry. The apparatus,[1] however, was more carefully designed, and the effect of changes in the ratio of the length of conducting paths was possibly more minutely tested out.[2] The sound was led to the ears separately by the two arms of a rectangle made of tubes of glass and brass joined at the corners by India rubber tubing. The observer's head, in position, occupied the mid-point in the back of this rectangle. Opposite his head, in the mid region of the front of the rectangle, a section 120 cm. long was removed and in its place a section of T-tubing was inserted, the horizontal arm of which was small enough in diameter to slide freely within the main tube, and long enough to permit the perpendicular arm to be moved 60 cm. on each side of the median plane. The perpendicular arm ended in a funnel-shaped collector, in front of which the tuning-fork was sounded. A centimeter scale was mounted behind the T-tube, upon which could be read the displacements of the perpendicular arm to the right or left of the median plane. The tubes leading to the ears ended in wooden receivers or ear-caps, which were pressed against the observer's head, and held in place by retort stands fastened to the table in front of the observer. The movements of the experimenter were shut off from the observer's view by a large screen across the median plane. When the funnel receiving the sound was placed in the median plane, the arms leading to the ears were of equal length, in most cases 317 cm. each. In this position it was found that the sound was located in the median plane. When the funnel was displaced by amounts varying from $0—\lambda/4$ ($\lambda=$ wave length) or $\lambda/2—3\lambda/4$, the sound was referred to the side toward which the displacement had been made. When it

[1]Apparatus somewhat similar to that used by Wilson and Myers is described by Urbantschitsch (Arch. f. d. ges. Physiol., 1881, XXIV, 579-585).

[2]Sylvanus Thompson (Philos. Mag., Ser. V, Vol. VI, 1878, pp. 386–387) worked in much the same fashion as Wilson and Myers, but with less minute measurement. The ends of a curved copper wire 3 ft. long, bent into two rings, were inserted one into each of the observer's ears. It was found that when the stem of a vibrating fork was set on this wire at the mid point, the sound seemed to come from the ends of the wire in each ear. A change of an inch and a half from this position produced a sufficient difference in the length of the path travelled by the sound to cause it to reach the two ears in complete difference of phase. Given in this position, the sound seemed to come from the back of the head. When the sound was given in intermediate positions, the effect was of a mixed character; part of the sound seemed as if located in the ears themselves, and part of it seemed to come from the back of the head. No change in this result was observed with forks of different pitches, providing that the proper differences in length of path were chosen.

was displaced by amounts varying from $\lambda/4$—$\lambda/2$ or $3\ \lambda/4$—λ, the sound was referred to the side opposite to that toward which the displacement had been made. The same relations between the reference of the sound and the displacements of the stimulus were observed to hold for simple multiples of λ. Thus it was found that when the stimulus is displaced either to the right or left of the median plane, the sound is successively referred, as the displacement is increased, first to the side toward which the displacement is made, back to the median plane, to the opposite side, and back to the median plane, repeating the cycle when the displacement reaches an amount exceeding one wave length.

In explaining these results, Wilson and Myers agree with Rayleigh that the localization of tones of low pitch is dependent upon the difference in the phase of vibration in which the sound waves reach the two ears. They do not, however, believe it is necessary to assume that the localizing clue is a direct recognition of phase difference by the two ears. They contend that "while binaural differences in phase are a primary cause of the observed lateral effects, these effects are ultimately referable to binaural differences in intensity." The stimulus in either ear is a resultant of two vibrations, one communicated directly to the ear, the other indirectly, through bone conduction from the opposite ear. The resultant, now stronger in one ear, now in the other, now equal in both ears, because of progressively changing phase differences between the direct and transmitted waves, determines the direction-reference. Suppose, as in the case of the Rayleigh experiments, two sound-waves of equal amplitude but of unequal frequency enter the two ears. Then from agreement to opposition the faster wave will lead the slower in phase, and from opposition to agreement the converse will be true. When the faster is leading, the resultant of the direct and transmitted waves in the ear receiving the faster wave will be of greater intensity than in the ear receiving the slower wave, and the total sound mass will be referred to that side. Similarly, when the slower leads in phase, the resultant will be stronger in the ear receiving the slower wave, and the localization will occur on that side. When, however, the two waves are in opposition or agreement, the resultants in both ears will be equal, and the localization will be in the median plane, as the intensity theory requires. Since, as they believe, this hypothesis satisfactorily explains the results of Rayleigh's experiments, they do not think that these experiments should be considered as affording differential evidence for the phase-difference theory. Nor do they claim differential value for their own experiments. With reference to physical features alone, both hypotheses are

capable of explaining both sets of results. Wilson and Myers, however, claim an advantage for their hypothesis on the ground of its greater plausibility and of the auxiliary facts that can be cited in its support. On the ground of plausibility, they maintain that their hypothesis is in better accord with the prevailing conception of the origin and nature of nervous impulses. For example, Rayleigh states:[1] "It seems no longer possible that the vibratory character of sound terminates at the outer ends of the nerves along which the communication with the brain is established. On the contrary, the processes in the nerve must in themselves be vibratory, not in the gross mechanical sense, but with the preservation of the period and retaining the characteristic of phase—a view advocated by Rutherford as long ago as 1886." Wilson and Myers believe that there is too much evidence of the specific functioning of end-organs to be overweighed by the results of Rayleigh's experiments. A special sense-organ may be excited not only by the stimuli to which it is especially adapted to respond ("adequate" stimuli), but also by "inadequate" stimuli; for example, electrical, chemical, and mechanical. "Inasmuch as the sensations are similar despite the diverse character of the stimuli, we have hitherto believed that the impulses ascending a sensory nerve depend on the mode of response of the end organ and not directly on the character of the stimulus." By way of auxiliary facts, they cite the results of Mader,[2] the tuning-fork experiment of Weber, and its modification suggested by Schaefer,[3]

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[1]Philos. Mag., Ser. 6, Vol. XIII, 1907, pp. 224-225.

[2]In Mader's experiments (Sitzungsber. d. kais. Akad. d. Wissens., Wien, 1900, Bd. CIX, Abth. 3, S. 37-75) two tones of nearly identical pitch were separately led one to each ear hole of a skull. A microphone applied to the roof of the skull gave evidence of beats. This is cited as presumptive evidence that the tones were actually passing across the roof of the skull from one ear to the other. (Both tones, however, were generated in the same room, hence there is no guarantee that the microphone was not acted upon by beats in the air wave.)

[3]Schaefer, K. L.: Zeitschr. f. Psychol. u. Physiol. d. Sinnesorg. 1891, Bd. II, S. 111-114. Wilson and Myers (*Op. cit.*, p. 318) describe this experiment as follows: "A fork, fixed at some distance from one side of the observer, is very gently struck. The observer listens, and notes when the dying tone has become quite inaudible. He then inserts an appropriately attuned resonator into the ear which is nearest the fork; whereupon, the tone is at once softly heard again on that side, as if it came from the resonator. If the meatus of the more distant ear be now closed, the tone becomes at once stronger, and its localization approaches the median plane. If the meatus be then re-opened, the tone immediately leaps back again to the ear in which the resonator is inserted."

Mach has suggested that when a tuning-fork is placed on the vertex, and the meatus of one ear is closed, the tone is localized to that side, because the sound travelling by bone conduction to that ear not only stimulates the cochlea, but sets up in the meatus vibrations which are reflected back and intensify the sound in that ear.

as evidence of bone conduction[1] under conditions similar to those in their own and in Rayleigh's experiments.[2]

As was stated earlier in the paper, this review will be concluded by a brief résumé of the arguments that have been advanced, up to the present time, for the binaural ratio as a factor in auditory localization. They are as follows. (1) Confusion points are found in the median plane and in the planes parallel to it on either side (Rayleigh,[3] von Kries and Auerbach,[4] Pierce,[5] and Starch[6]). (2) Monaural localization is inferior to binaural localization. (Politzer,[7] Arnheim,[8] Preyer,[9] Bloch,[10] von Bezold,[11] Smith,[12] Angell and Fite,[13] and Starch.[14]) Politzer, Arnheim, Preyer, and Bloch worked with cases of monaural hearing artificially produced; von Bezold, Angell and Fite, and Smith worked with pathological cases. Starch worked with two observers in which the defect was artificially produced, and two in which it was pathological. For Politzer, Arnheim, Preyer, Smith, and Angell and Fite, the test used was accuracy of localization; for Bloch it was the size of the j. n. d.; and for Starch it was both accuracy of localization and the size of the j. n. d.

(3) The greatest accuracy of localization occurs at points where a change of direction produces the greatest change in

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[1]Against bone conduction *vide* the experiments and conclusions of Cross and Goodwin (this paper p. 260.)

[2]There may be cited additional casual advantages, so obvious, however, as to be scarcely worthy of mention. (1) Wilson and Myers's explanation does not involve the assumption of any new power on the part of the ear, hence it has the advantage of systematic simplicity. (2) Introspective analysis does not show any aspect of the sound sensation, or any new sensation simultaneous with the sound sensation, corresponding to difference of phase.

[3]Rayleigh, Lord: *Acoustical Observations, Perception of the Direction of a Source of Sound,* Philos. Mag., Ser. 5, Vol. III, 1877, pp. 456-458.

[4]*Op. cit.,* p. 330, 336.

[5]*Op. cit.,* pp. 56-78.

[6]Psychol. Rev., Monog. Suppl., Vol. IX, 1908, p. 53.

[7]*Op. cit.,* p. 231-236.

[8]Arnheim: Beiträge zur Theorie der Lokal. von Schallemp. mittl. der Bogengänge. Diss, Jena, 1887.

[9]Preyer: *Die Wahrnehmung der Schallrichtung mittelst der Bogengänge,* Pflüger's Archiv, XL, 1887, pp. 618-619. It will be remembered, however, that Preyer and Arnheim believed that the localization is in terms of space feelings aroused directly by the action of the sound wave upon the semicircular canals.

[10]*Op. cit.,* p. 59-73.

[11]*Op. cit.,* p. 486-487.

[12]*Op. cit.,* p. 542.

[13]*Op. cit.,* pp. 225-246 and 449-458. Angell and Fite claim that a considerable degree of inferiority of monaural hearing exists only in the case of unpracticed monaural subjects. Monaural subjects can be practiced up to the point of localizing almost as well as the unpracticed normal subject.

[14]Psychol. Rev., Monog. Suppl., IX, 1908, pp. 40-48.

the binaural ratio, *i. e.*, in front and back near the median plane; and the poorest localization occurs where a change of direction produces the least change in the binaural ratio, *i. e.*, at the sides, near the aural axis[1] (Bloch,[2] and Starch[3]).

(4) A difference in the amount of collection of the sound-wave at the orifices of the ears determines the localization to the side receiving the greater energy of the wave (Thompson,[4] and Kessel[5]).

The total sound-mass is referred to the side of the stronger stimulus when two sounds, one stronger than the other, are given to the two ears. (Steinhauser,[6] Tarchanoff,[7] and Matsumoto[8]).

When two tuning-forks sounding with equal intensity are placed one on each side of the head, but one nearer to the ear than the other, the total sound-mass is referred to the side on which the nearer fork is located (Stenger[9]).

When two tuning-forks, sounding with equal intensity and located in the aural axis on either side at the same distance from the ears, are swung in unison from left to right and right to left, a transfer in the localization of the total sound mass takes place following the rhythm of the swing. When both are swinging to the left, the sound is referred to the right, and, conversely, when both are swinging to the right, the localization is on the left. When both are swinging with equal speed in opposite directions, the localization is in the median plane (Fechner[9]).

When two vibrating bodies are in contact with the head or very near to it, and the energy of vibration is unequal, the

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[1]Starch (*Op. cit.*, p. 52.) phrases this as follows. "The accuracy of localization is greatest where slight changes in the ratio are most readily perceived, *i. e.*, in front and back. Localization is poorest where changes in the ratio are not so easily perceived, *i. e.*, on the sides, in the region of the aural axis."

[2]*Op cit.*, pp. 31, 35.

[3]Psychol. Rev., Monog. Suppl., Vol. VI, No. 4, 1904-05, pp. 11-12 and 44; *ibid.*, Vol. IX, No. 2, 1908, pp. 52-53.

[4]Thompson: Philos. Mag., Ser. 5, Vol. VIII, 1879, p. 386; *ibid.*, Vol. XIII, 1882, p. 412.

[5]*Op. cit.*, p. 120.

[6]*Op. cit.*, pp. 188-189. Steinhauser used as the source of sound an instrument called by him the homophone. This instrument consisted of two organ pipes of the same pitch, one of which was supported near to each ear on the level with it. The intensity of the sound was regulated by means of valves controlling the pressure of the air blast used to excite it.

[7]*Op. cit.*, p. 354.

[8]*Op. cit.*, p. 18. Matsumoto used two telephone receivers placed opposite the two ears, one on each side. The intensity of the sound in each ear was controlled by a sliding inductorium.

[9]Stenger: *Op. cit.*, p. 223.

[10]Fechner, G. T.: *Op. cit.*, p. 543.

sound is localized within the head but is referred to the side receiving the greater energy of vibration (Urbantschitsch,[1] and Thompson[2]).

When the stem of a vibrating tuning fork is placed on the vertex of the skull, the tone is localized somewhere midway between the two ears; but if the meatus of one ear is stopped and the wave is reflected back toward the internal ear, the sound is transferred immediately to that side (Weber[3]).

When a tuning-fork is faintly sounded on one side and heard by the ear on that side by means of a resonator, the sound is referred to that side; but when the meatus of the opposite ear is stopped, the sound approaches the median plane (Schaefer[4]).

One of two fusing sounds may be placed in either of the lateral quadrants without altering the localization of the fusion (Pierce[5]).

II. Experimental

A. The Demonstration of the Binaural Ratio as a Factor

(a) *Lines of Argument.* The object of this paper is to add three lines of argument to those mentioned above. (1) Observers having a natural difference in sensitivity of the two ears show a constant tendency to displace the source of sound toward the axis on the side of the stronger ear; and, conversely, observers without this difference in sensitivity show no consistent tendency toward right or left displacement. (2) Changes in the ratio of sensitivity of the two ears, produced by plugging either ear, are followed by corresponding displacements of the sound toward the more sensitive ear. (3) A natural tendency toward right or left displacement can be corrected by making the proper change in the ratio of sensitivity of the two ears.

The principle involved in the second argument is not entirely new.[6] It aims at a direct and systematic correlation

[1]Urbantschitsch: *Lehre von der Schallempfindung,* Pflüger's Archiv, XXIV, 1881, 579.

[2]Thompson, *On Binaural Audition,* Philos. Mag., Ser. 5, Vol .IV, 1877, pp. 274-276; *Phenomena of Binaural Audition, ibid.,* Ser. 5, Vol. VI, 1878, pp. 383-391.

[3]Weber: *Op. cit.,* p. 42.

[4]Schaefer: *Op. cit.,* pp. 111-114.

[5]Pierce: *Op. cit.,* pp. 63 and 147.

[6]It might probably be said that the principle involved in the first line of argument is also not entirely new. Results of monaural localization have been reported by numerous investigators; and occasional mention has been made of a suspected influence of difference in sensitivity of the two ears upon the results obtained in cases of binaural localization. (For the best example of this, *vide* Seashore: *Localization of Sound in the Median Plane,* Univ. of

between the intensity of the sound as heard by the two ears, and the direction in which it is referred. This has not been attempted before, although it has been shown more or less definitely that a difference in the energy of the sound-wave delivered to the two ears affects localization. Thompson,[1] for example, with his pseudophone, tried to produce a difference in the energy of the stimuli given to the two ears by means of the way in which the shell-shaped collectors were turned with reference to the direction of the stimulus, and to show thereby that the localization was determined toward the side receiving the stronger stimulation. Though the underlying principle of this general line of argument is not new, the writers have followed it up for the following reasons. (1) Its possibilities for demonstrating the binaural ratio as a factor in localization have not been fully utilized. (2) In order to confirm the intensity theory, it is necessary to show a definite correlation between the ratio of intensity of sensation, and the direction in which the sound is referred. The method of varying the sensitivity of the two ears gives a much safer and more direct means of establishing this correlation than is given by varying the intensity of the stimuli. The writers find, for example, that the ears of many people vary greatly in sensitivity. In fact, so far as his experience goes, it is more common to find a difference than to find the ears of

Iowa Studies in Psychol., 1899, II, p. 49). But for theory, monaural hearing presents a very different case from difference in sensitivity in binaural hearing (when working with monaural hearing the binaural factors drop out entirely); and, furthermore, no systematic attempt has ever been made to utilize differences in sensitivity as a means of demonstrating the influence of the binaural ratio.

For reports on monaural localization, see Politzer (*Loc. cit.*); Preyer (*Die Wahrnehmung der Schallrichtung mittelst der Bogengänge,* Pflüger's Archiv, XL, 1887, S. 586); Arnheim (*Beiträge zur Theorie der Lokal. von Schallempf. mittelst der Bogengänge,* Diss. 1887.); Münsterberg (*Raumsinn des Ohres,* Beiträge zur Exp. Psy., Bd. II, 1889, S. 182), von Bezold (*Urteilstäuschungen nach Beseitigung einseitiger Harthörigkeit,* Zeit. f. Psy. u. Physiol. II, 1890, S. 486); Schäfer (*Ein Versuch über die interkranielle Leitung leisester Töne von Ohr zu Ohr,* Zeit. f. Psy. u. Physiol. II, 1891, S. 111); Smith (*How do we Detect the Direction from which Sound Comes?* Cincin. Lancet-Clinic, N. S. XXVIII, 1892, 542); Angell and Fite (*The Monaural Localization of Sound,* Psy. Rev. VIII, 1910, 225-266, and *Further Observations on the Monaural Localization of Sound, Ibid.,* 449-458); and Starch (*Perimetry of the Localization of Sound,* Psy. Rev. Mon. Supp. IX, 2, 1908, 1-55). For mention of a suspected influence of difference in the sensitivity of the two ears upon localization, see Pierce (*Op. cit., p.* 106), and Starch (*Op. cit.,* pp. 43-44). An influence of difference of sensitivity of the two ears is suggested by Arnheim (*Op. cit.,* p. 10, note) to explain his results when working with monaural hearing artificially produced. The left ear was found to have the superior power to localize correctly. He thought this might be due to its better blood supply. Pierce speaks against this part of Arnheim's work (*Op. cit.,* p. 107).

[1]*Op. cit.,* pp. 385-390.

approximately equal sensitivity.[1] A method, then, which seeks to vary the intensity of the sound as heard by the two ears, and does not take into account their probable difference in sensitivity, is obviously at fault; for there is no guarantee that a slight difference in the energy of the sound-waves delivered to the two ears, such as was produced by a different setting of the small shell-shaped collectors of Thompson's pseudophone, will be sensed as the relative intensities of the stimuli would indicate. If one ear should be more sensitive than the other, the two sound-waves, although one is stronger than the other, may be sensed as equal in intensity; or the ratio indicated by the stimuli may be reversed. Because, then, of the common occurrence of a natural difference in sensitivity between the ears, a method that attempts to measure the ratio of intensity of the sensations experienced by the ratio of intensity of the stimuli given, does not afford a safe basis for a correlation between the intensity of the sound as heard by the two ears and its localization. (3) Apart from the propriety of method, a third reason for continuing this line of attack is that the results reported from it have been too vague and uncertain to give much support to the intensity theory. For example, (a) the shell-shaped collectors in Thompson's pseudophone were assumed to collect more sound when given one direction than when given another; but there was no objective determination of how much they varied the intensity of the wave impinging upon the tympanum, or whether they varied it at all. No proper basis was laid even for a correlation of ratio of intensity of the two stimuli with the direction in which the sound was referred. (b) The method used for recording Thompson's localizations was indefinite, and his report of results is vague and uncertain. In short, a characteristic displacement of the sound toward the side receiving the more intensive stimulation is expressed (in the paper of 1879) as a matter of belief rather than as an established fact.[2]

(b) *Description of Method and Apparatus.* The writers were led to make this study by the results of tests they had been conducting on the relative sensitivity of the two ears in different people. The large number of subjects who were found to have a marked difference in sensitivity seemed to make possible a determination of whether or not the hearing of a

[1]Fechner, investigating the relative sensitivity of the two ears (*Ueber die ungleiche Deutlichkeit des Gehörs auf linkem und rechtem Ohre,* Berichte der kgl. Sächs. Ges. der Wiss. Math.-phys. Classe, XII, 1860, 166-174), found that out of 215 persons examined only 51 had ears of approximately equal sensitivity.

[2]*Op. cit.*, pp. 388-390.

sound more strongly by one ear than the other leads to constant errors in localization. Assuming that the binaural ratio is a factor in localizing, there seem *a priori* to be two possibilities relative to this question. (a) The subject so affected may, in proportion to his defect, show a constant tendency to displace the sound towards the aural axis on the side of the more sensitive ear, or (b) this tendency may have been wholly or in part corrected in the subject's past experience, through the influence of the space reference of other sense organs, in such a fashion that the false ratio has shown a tendency to become associated with the true reference. If so, the amount of the constant error probably should sustain some ratio to the length of time the defect had existed. If, for example, it were congenital or contracted very early in life, one might expect less error in localization than if it were of recent occurrence. Unfortunately the subjects, up to the time of these tests, were not aware of their defect, consequently no data of the sort were available. The effect of recency of defect, however, came out strongly in the experiments in which the ratio was varied by artificial means. Differences in sensitivity, artificially produced, exerted a much more marked influence upon localization than did approximately equal differences due to natural defect.

Artificial variations were produced both upon defective subjects and upon subjects in whom the sensitivity of the two ears was approximately equal. In both cases the effect was marked and consistent. In case of the normal subjects, in turn first one ear was made more sensitive, then the other. In case of the defective subjects three variations were introduced. (a) The defect was exaggerated, *i. e.*, the difference in sensitivity was rendered greater by plugging the less sensitive ear.[1] (b) An effort was made to correct the defect by decreasing the sensitivity of the stronger ear. Our object here was to establish a ratio of sensitivity that should eliminate any approach to a constant tendency to displace the sound in either direction. This was a procedure involving many trials and much patience. Our first idea was that this result should be attained by equating the sensitivity of the two ears. This device, however, in case of the subjects

[1]In all cases of plugging one ear, care was taken that monaural hearing was not produced. Before the observation began, both ears were firmly closed by the hands or some other effective means, until the stimulus used in the localizing experiments could no longer be heard, whatever position it might be given in the system used. The plugged ear was then uncovered, and the stimulus given at the most remote positions to be used in the experiment which was to follow. In no case was the observer unable to hear the sound.

used, overshot the mark. When the sensitivity of the stronger ear was decreased until it approximately equalled that of the weaker ear, a constant tendency to displace towards the normally weaker ear resulted. A compromise position then had to be sought. We finally succeeded in getting, with each subject, a ratio such that the error, roughly speaking, was apparently about as much and as frequently to one side as to the other of the true location. (c) A third variation was to plug the stronger ear until it became less sensitive than the weaker ear.

In all of our experiments, in order to guard against a wrong correlation of ratio with localization error, due to possible variations in sensitivity from day to day, or even from the beginning to the end of the experiment, sensitivity determinations were made at each sitting both immediately before and immediately after the localizing tests were made.

The ratio of sensitivity was obtained by comparing the limen of sound for the two ears. The observer was blindfolded and required to bite an impression previously made in a wax mouth-board. A wooden bar was supported in the line of the axis of the two ears, one end reaching as near as possible to the ear that was being tested. The other ear was carefully plugged. A watch was carried out along the bar until the limen was reached. An average of the results obtained by the method of approach and recession was taken as the final liminal distance, and the ratio of these distances was taken to represent the ratio of sensitivity of the two ears. To make sure that the plugged ear was not functioning in these tests, the watch was held as closely as possible to it without touching the lobe and the observer required to tell whether it could be heard or not.

The localizing experiments were carried on by means of the Titchener sound-cage. A Galton whistle set at 20,000 vibrations per second was used for the stimulus. As to devices for indicating the location of the sound, the pointing method, the chart method, and a combination of the two were used at different times. The authors have not made an exhaustive study of the relative merits of these methods but is inclined to prefer, on the basis of what they have done, a careful use of the pointing method alone. Any method involving the use of the chart has, in his experience, fostered a tendency on the part of the observer to delay the reference, to become uncertain and hesitating, to reason and debate with himself rather than to let whatever sensory mechanism for localizing with which nature may have provided him work itself out automatically. The errors arising from this tendency are, in our opinion, greater and more capricious than those from

wrong pointing, if proper care is exercised to make sure that the observer is pointing as he intends to point. The question of methods of recording, however, makes little difference for or against the validity of our demonstration; for (a) the constant displacement tendency appears whatever the method used, and (b) no method, however comprehensive its faults, could account for the consistent throw in opposite directions in case of different observers, or in the case of the same observer, when first one ear then the other is made more sensitive.

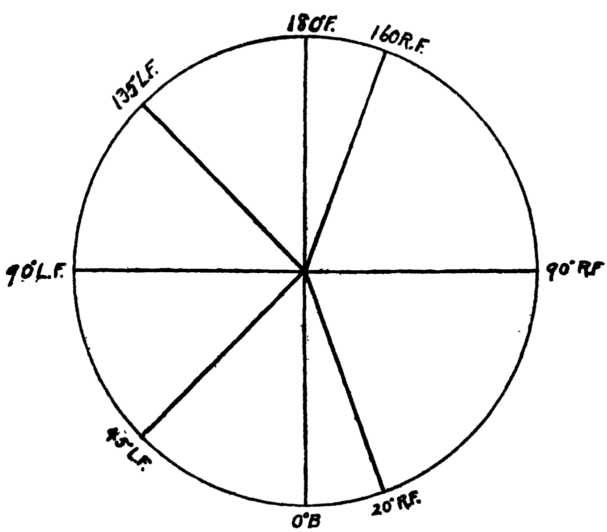

FIG. III

0° B.	180° F.
45° R. F. or L. F.	135° R. F. or L. F.
50° R. F. or L. F.	130° R. F. or L. F.
60° R. F. or L. F.	120° R. F. or L. F.
70° R. F. or L. F.	110° R. F. or L. F.
150° R. F. or L. F.	30° R. F. or L. F.
160° R. F. or L. F.	20° R. F. or L. F.

Thus far results have been obtained from ten observers in the investigation proper. In addition, the writers have roughly used, at one time or another for two years, all of the variations as a part of the drill course in his undergraduate laboratory.

(c) *Results.* The following tables have been compiled from the results of three of these observers, who were selected as representative: the Misses Friend (*F.*), Root (*R.*), and

Sharp (*S.*). Tables I-XII, inclusive, show the results of the experiments devised to demonstrate the importance of the binaural ratio as a factor in auditory localization. In all the tables given throughout the paper, locations in the horizontal plane are expressed in terms of the readings of the Titchener sound-cage. In this system of reference, the zero point is placed in the median plane, behind; the 90° points in the aural axis, right and left; and the 180° point in the median plane in front. It was found more convenient, however, in the vertical planes, to deviate from the scale of the sound-cage; the zero point was taken in the plane of the aural axis, and directions were read 90° up and down. Displacements to right or left were estimated from the actual position of the stimulus, or from its corresponding point front or back, as the case happened to be. For example, a stimulus given at 160° right front (R. F.) might be referred by the observer either to 160° R. F. or to its corresponding point, 20° R. F., without the reference being considered a displacement toward either ear. But if a stimulus were given at 160° R. F. and

TABLE I

Observer *F*. Showing the influence of the binaural ratio upon the localization of clangs. Natural sensitivity series. Liminal distance for right ear, 40 cm.; for left ear, 40 cm. Ratio, Left: Right = 1. Stimulus, Galton whistle, 20,000 vibrations per second.

Set		Heard		Displacement toward axis of right ear	Displacement toward axis of left ear
Horizontal	Vertical	Horizontal	Vertical		
45° R F	0°	50° R F	0° d	5°	
135° L F	0°	50° L F	8° d		5°
0° B	0°	0° B	5° d	0°	0°
135° R F	0°	125° R F	5° u	10°	
45° L F	45° u	50° L F	5° u		5°
180° F	0°	20° L F	0°		20°
135° L F	45° u	40° L F	20° d	5°	
45° L F	45° d	50° L F	40° d		5°
150° R F	0°	145° R F	0°	5°	
0° B	45° u	10° R F	0°	10°	
45° R F	45° u	50° R F	0°	5°	
180° F	45° u	0° B	40° u	0°	0°
135° R F	45° u	135° R F	30° u	0°	0°
150° L F	45° u	35° L F	25° u		5°
0° B	90° u	20° R F	20° u	20°	
70° L F	0°	70° L F	0°	0°	0°
50° R F	45° d	120° R F	5° d	10°	
70° R F	0°	80° R F	0°	10°	
0° B	0°	0° B	0°	0°	0°

Average displacement from median plane 2.1° (right).

were referred either to 140° R. F. or to 40° R. F., the reference would be considered a displacement toward the axis of the right ear. Fig. 3 shows a diagram of the horizontal plane of reference, with two pairs of corresponding points represented. Below it are given readings in degrees for the corresponding points used in the experiments.

Tables I, II, and III show the results for the natural difference in sensitivity of the two ears for Observers *F.*, *R.*, and *S.*, respectively. In each case, the liminal distance for the

TABLE II

Observer *R.* Showing the influence of the binaural ratio on the localization of clangs. Natural sensitivity series. Liminal distance: right ear, 18.5 cm.; left ear, 72 cm. Ratio, Left : Right = 4. Stimulus, Galton whistle, 20,000 vibrations per second.

Set		Heard		Displacement toward axis of stronger ear	Displacement toward axis of weaker ear
Horizontal	Vertical	Horizontal	Vertical		
45° R F	0°	25° R F	30° d	20°	
135° L F	0°	50° L F	30° d	5°	
0° B	0°	15° L F	50° d	15°	
135° R F	0°	40° R F	38° d	5°	
45° L F	45° u	60° L F	35° d	15°	
180° F	0°	35° L F	20° d	35°	
135° L F	45° u	70° L F	38° d	25°	
45° L F	45° d	55° L F	33° d	10°	
150° R F	0°	40° R F	42° d		10°
0° B	45° u	35° L F	35° d	35°	
45° R F	45° u	10° R F	45° d	35°	
180° F	45° u	30° L F	42° d	30°	
135° R F	45° u	15° R F	45° d	30°	
150° L F	45° u	40° L F	35° d	10°	
0° B	90° u	50° L F	10° d	50°	
70° L F	0°	70° L F	10° d	0°	0°
50° R F	45° d	15° R F	50° d	35°	
70° R F	0°	50° R F	38° d	20°	

Average displacement toward axis of stronger ear, 20.3°

ticking of a watch was determined for each ear both before and after the observations, and the ratio of sensitivity was computed from these distances. For observer *F.* this distance was found to be 40 cm. for each ear. Estimated in terms of these distances, then, the observer's ears were approximately equal in sensitivity. As the tables show, the ears of observers *R.* and *S.* were found to be of unequal sensitivity. It will be noted that a rough correspondence holds in each case between the ratio of sensitivity of the ears, and the observer's characteristic localizing tendency.

TABLE III

Observer *S*. Showing the influence of the binaural ratio on the localization of clangs. Natural sensitivity series. Liminal distance: right ear, 97 cm.; left ear, 33 cm. Ratio, Right : Left = 2.9. Stimulus, Galton whistle, 20,000 vibrations per second.

Set		Heard		Displacement toward axis of stronger ear	Displacement toward axis of weaker ear
Horizontal	Vertical	Horizontal	Vertical		
135° R F	0°	5° R F	5° d		40°
45° L F	0°	30° L F	0°	15°	
150° L F	45° d	10° L F	0°	20°	
0° B	45° u	0° B	45° u	0°	0°
180° F	45° d	5° L F	35° d		5°
45° R F	45° u	50° R F	35° u	5°	
135° R F	45° u	45° R F	52° u	0°	0°
160° L F	0°	0°	0°	20°	
0° B	90° u	30° R F	12° u	30°	
70° L F	0°	65° L F	0°	5°	
135° L F	0°	25° L F	0°	20°	
45° R F	45° d	10° R F	15° d		35°
0° B	90° u	25° R F	12° u	25°	
60° R F	0°	70° R F	18° u	10°	
150° R F	0°	50° R F	15° u	20°	
45° L F	45° u	0° B	2° d	45°	
60° L F	45° u	5° L F	30° u	55°	
160° R F	0°	25° R F	10° u	5°	
60° L F	45° d	40° L F	10° d	20°	
0° B	0°	0° B	5° d	0°	0°

Average displacement toward axis of stronger ear, 10.7°.

Tables IV and V show the effect upon localization for observers *R*. and *S*., produced by exaggerating the natural ratio of sensitivity of the two ears by plugging the weaker ear. It will be noticed that in each case the observer's tendency to displace the sound toward the axis on the side of the stronger ear is increased. For example, with the natural difference in sensitivity, Observer *R*.'s average displacement toward the axis on the side of the stronger ear was 20.3° (Table II); with the exaggeration of the natural difference, the average displacement became 31.6° (Table IV). For Observer *S*., the average displacement toward the axis on the side of the stronger ear, with the natural difference in sensitivity, was 10.7° (Table III); with the exaggeration of this difference, the displacement was increased to 17.2° (Table V).

Tables VI and VII show the effect upon localization, for Observers *R*. and *S*., produced by, plugging the stronger ear until it became less sensitive than the weaker ear. The result in each case was to change the characteristic displacement to the opposite side—now the side of the stronger ear. For

example, for Observer *R.*, when the ratio was changed from left: right=4, to right: left=6.2, the average displacement of 20.3° toward the axis on the side of the left ear was changed to an average displacement on the side of the right ear of 34.4°. And for Observer *S.*, when the ratio right: left= 2.9 was changed to left: right= 3.8, the average displacement was changed from 10.7° toward the right to 34.6° toward the left.

TABLE IV

Observer *R.* Showing the influence of the binaural ratio on the localization of clangs. Artificial sensitivity series. Right ear plugged. Liminal distance: right ear, 3 cm.; left ear, 71 cm. Ratio, Left : Right=23.6. Stimulus, Galton whistle, 20,000 vibrations per second.

Set		Heard		Displacement toward axis of stronger ear	Displacement toward axis of weaker ear
Horizontal	Vertical	Horizontal	Vertical		
0° B	0°	30° L F	40° d	30°	
45° R F	0°	10° L F	35° d	55°	
180° F	0°	60° L F	10° d	60°	
135° L F	0°	55° L F	15° d	10°	
60° L F	0°	70° L F	15° d	10°	
0° B	45° u	40° L F	48° d	40°	
135° R F	0°	45° R F	40° d	0°	0°
180° F	45° u	40° L F	50° d	40°	
45° L F	45° d	55° L F	12° d	10°	
135° R F	45° d	40° R F	43° d	5°	
0° B	45° d	35° L F	25° d	35°	
180° F	45° d	30° L F	15° d	30°	
45° R F	45° u	25° L F	45° d	70°	
135° L F	45° u	50° L F	15° d	5°	
45° L F	45° u	60° L F	40° d	15°	
135° R F	45° u	15° L F	32° d	60°	
0° B	90° u	15° L F	15° d	15°	
45° R F	45° d	35° L F	18° d	80°	

Average displacement toward axis of stronger ear, 31.6°.

Tables VIII and IX show the effect upon localization made by producing artificial differences in the sensitivity of the ears for Observer *F.*, whose natural sensitivity is approximately equal for both ears. When the left ear was plugged until the ratio right: left=4.3 was obtained, the average displacement toward the axis on the side of the right ear was found to be 17°. And when the right ear was plugged until the ratio left: right = 4.1 was obtained, the average displacement toward the side of the left ear was found to be 18.2°. It will be remembered from Table I that the average of the localizations for this observer with natural hearing showed a displacement toward the right of 2.1°.

TABLE V

Observer *S.* Showing the influence of the binaural ratio on the localization of clangs. Artificial sensitivity series. Left ear plugged. Liminal distance: right ear, 97 cm.; left ear, 10 cm. Ratio, Right : Left = 9.7. Stimulus, Galton whistle, 20,000 vibrations per second.

Set		Heard		Displacement toward axis of stronger ear	Displacement toward axis of weaker ear
Horizontal	Vertical	Horizontal	Vertical		
0° B	0°	45° R F	0°	45°	
45° R F	0°	35° R F	0°		10°
135° L F	0°	5° L F	7° d	40°	
180° F	0°	10° R F	8° d	10°	
135° R F	0°	20° R F	0°		25°
45° L F	45° u	5° L F	14° d	40°	
0° B	45° u	50° R F	15° u	50°	
135° R F	45° u	40° R F	8° u		5°
135° L F	45° u	25° L F	12° u	20°	
180° F	45° u	30° R F	20° u	30°	
45° R F	45° u	52° R F	30° u	7°	
45° L F	45° d	35° L F	8° d	10°	
0° B	45° d	20° R F	8° u	20°	
45° R F	45° d	60° R F	15° u	15°	
135° L F	45° d	45° L F	30° u	0°	0°
180° F	45° d	20° R F	15° u	20°	
135° R F	45° d	45° R F	10° u	0°	0°
0° B	90° u	40° R F	10° u	40°	
60° L F	0°	40° L F	10° u	20°	

Average displacement toward axis of stronger ear, 17.2°.

Table X shows the effect upon localization, in the case of Observer *R.*, of an attempt to equate the sensitivity of the ears. The natural ratio of sensitivity for this observer (Table II) was left: right = 4. When this was changed by plugging the left ear until the ratio right: left = 1.02 (18.5 ÷ 18.2) was obtained, there resulted an average displacement 31.4° toward the axis on the side of the right ear. Results of this kind were obtained for all observers. A characteristic tendency to displace the sound to right or left cannot be corrected by equating the ratio of sensitivity of the ears. A value must be obtained somewhere between the natural ratio and equal sensitivity.[1]

[1]That the effect of equating the sensitivity should overshoot the mark is not at all strange. If one ear naturally hears more loudly than the other, an equal intensity of sensation has never been associated in the observer's experience with objects in the median plane, but always with some position displaced from the median plane toward the naturally weaker ear. Then when the stronger ear is plugged until it is of the same sensitivity as the weaker ear, sounds which can be heard as equally loud by both ears, *i. e.*, sounds coming from the median plane, will not be referred to that plane,

TABLE VI

Observer *R*. Showing the influence of the binaural ratio on the localization of clangs. Artificial sensitivity series. Left ear plugged. Liminal distance: right ear, 18.5 cm.; left ear, 3 cm. Ratio, Right : Left = 6.2. Stimulus, Galton whistle, 20,000 vibrations per second.

Set		Heard		Displacement toward axis of stronger ear	Displacement toward axis of weaker ear
Horizontal	Vertical	Horizontal	Vertical		
45° R F	0°	65° R F	0°	20°	
0° B	90° u	15° R F	42° d	15°	
180° F	45° d	25° R F	40° d	25°	
60° L F	0°	25° R F	40° d	85°	
135° R F	0°	40° R F	25° d		5°
45° R F	45° d	45° R F	18° d	0°	0°
135° L F	45° d	4° R F	40° d	49°	
0° B	45° d	30° R F	32° d	30°	
45° L F	45° d	55° R F	20° d	100°	
135° L F	45° u	5° R F	35° d	50°	
135° R F	0°	40° R F	20° d		5°
45° R F	45° u	50° R F	10° d	5°	
180° F	45° u	25° R F	38° d	25°	
45° L F	45° u	45° R F	42° d	90°	
135° R F	45° u	45° R F	45° d	0°	0°
0° B	45° u	45° R F	20° d	45°	
180° F	0°	25° R F	38° d	25°	
135° L F	0°	5° R F	28° d	50°	
0° B	0°	50° R F	40° d	50°	

Average displacement toward axis of stronger ear, 34.4°.

Tables XI and XII show the results of fairly successful attempts to correct this observer's tendency to displace sounds towards the left. In Table XII with a ratio left:right = 1.5 we find an average displacement of 2.1° towards the right; in Table XI with a ratio left:right = 2.1 we find an average displacement of 1.4° towards the left. The former tables thus show over-correction; the latter, under-correction.

B. THE RELATIVE IMPORTANCE OF INTENSITY AND TIMBRE AS FACTORS IN LOCALIZATION

In these experiments, tuning forks were used as the source of sound. The object was to find out to what extent the con-

but will be displaced toward the axis on the side of the weaker ear, because sounds of equal intensity have always had that connotation in the observer's past experience. Likewise, when the ears have been made equally sensitive by plugging the stronger, sounds which come from positions to either side of the median plane will always be displaced toward the naturally weaker ear, because now they are heard by the two ears with a relative loudness which, in the observer's past experience, has always connoted a position relatively nearer the weaker ear.

TABLE VII

Observer *S*. Showing the influence of the binaural ratio on the localization of clangs. Artificial sensitivity series. Right ear plugged. Liminal distance: right ear, 18 cm.; left ear, 70 cm. Ratio, Left : Right = 3.8. Stimulus, Galton whistle, 20,000 vibrations per second.

Set		Heard		Displacement toward axis of stronger ear	Displacement toward axis of weaker ear
Horizontal	Vertical	Horizontal	Vertical		
0° B	0°	30° L F	5° d	30°	
180° F	0°	30° L F	20° d	30°	
45° R F	0°	10° L F	5° d	55°	
45° L F	45° u	60° L F	5° u	15°	
0° B	45° u	33° L F	22° d	33°	
135° R F	0°	20° L F	5° d	65°	
135° L F	0°	50° L F	15° d	5°	
180° F	45° u	30° L F	0°	30°	
135° R F	45° u	20° L F	18° u	65°	
135° L F	45° u	65° L F	5° u	20°	
0° B	45° d	25° L F	0°	25°	
45° R F	45° u	35° L F	10° u	80°	
45° L F	45° d	50° L F	15° u	5°	
60° L F	0°	6° L F	5° u		54°
45° R F	45° d	30° L F	12° d	75°	
180° F	45° d	40° L F	12° d	40°	
135° R F	45° d	30° L F	5° d	75°	
0° B	90° u	30° L F	5° d	30°	

Average displacement toward axis of stronger ear, 34.6°.

ditions obtaining in the former experiments influence the localization of simple tones. Three cases are possible. (a) These conditions may exert no influence at all. We should then have to conclude that, in the former experiments, the binaural ratio produces its effect wholly as a difference in the timbre of the sound as heard by the two ears. That is, since timbre depends upon the number and the proportionate strength of the overtones in the clang, in case one ear is more sensitive than the other, the timbre of the sound heard by one ear will differ from that heard by the other ear because of the different number of overtones present in the two cases.[1] (b) The conditions may exert some influence, but not

[1]This view of the way the binaural ratio serves as a localizing clue was first advanced by Rayleigh in 1876, and later by Sylvanus Thompson (*Op. cit.*, p. 415) in 1882. Thompson says: "Judgments as to the direction of sound are based, in general, upon the sensations of different intensity in the two ears, but the perceived difference of intensity upon which a judgment is based is not usually the difference in intensity in the lowest or fundamental tone of the compound (or 'clang'), but upon the difference in intensity of the individual tone or tones of the clang for which the intensity difference has the greatest effective result in the quality of the sound . . . . It is completely open to doubt whether a pure simple tone heard in one ear could suggest any direction at all."

as much as was exerted upon the sound of the Galton whistle. In this case, we should have to conclude that differences of intensity both in the fundamental and in the overtones of the clang served as a localizing clue in our experiments. (c) They may exert an equal influence upon the sound of the tuning fork and upon the clang. This would indicate that differences in the intensity of the fundamental tone alone were operative as local signature.

TABLE VIII.

Observer *F*. Showing the influence of the binaural ratio on the localization of clangs. Artificial sensitivity series. Left ear plugged. Liminal distance: right ear, 39 cm.; left ear, 8 cm. Ratio, Right : Left = 4.9. Stimulus, Galton whistle, 20,000 vibrations per second.

Set		Heard		Displacement toward axis of stronger ear	Displacement toward axis of weaker ear
Horizontal	Vertical	Horizontal	Vertical		
45° R F	0°	70° R F	8° u	30°	
135° L F	0°	35° L F	0°	10°	
0° B	0°	35° R F	0°	35°	
135° R F	0°	50° R F	0°	5°	
45° L F	45° u	50° L F	0°		5°
180° F	0°	0° B	0°	0°	0°
135° L F	45° u	45° L F	30° d	0°	0°
45° L F	45° d	0° B	30° d	45°	
150° R F	0°	30° R F	5° d	0°	0°
0° B	45° u	10° R F	10° d	10°	
45° R F	45° u	45° R F	20° u	0°	0°
180° F	45° u	155° R F	10° u	25°	
135° R F	45° u	170° R F	20° u		35°
150° L F	45° u	35° L F	0°		5°
0° B	90° u	25° R F	0°	25°	
45° L F	0°	0° B	20° d	45°	
0° B	45° d	40° R F	10° d	40°	
180° F	0°	15° R F	10° u	15°	

Average displacement toward axis of stronger ear, 17°.

The stimulus was given as follows in these experiments. The observer, blindfolded, with head firmly clamped and ears tightly closed, sat in position in the sound-cage. A heavy unmounted tuning fork of 480 vibrations per second and a cylindrical resonator were used as the source of sound. These were substituted for the telephone receiver of the sound-cage. The fork was plucked by the fingers covered by a chamois glove, and was allowed to vibrate for a few seconds to allow possible high overtones, harmonic or inharmonic, to die out. It was then held over the mouth of the resonator.

As soon as the tone became audible, the observer's ears were uncovered and the sound was listened to for about one second, at the end of which time the fork was removed from the mouth of the resonator, and the direction in which the sound was heard was indicated by the observer. In no case were any of the noises attendant upon the stimulation of the fork heard; and a tone as simple as a tuning fork is capable of giving was obtained. The duration of the stimulus was roughly the same

TABLE IX

Observer *F*. Showing the influence of the binaural ratio on the localization of clangs. Artificial sensitivity series. Right ear plugged. Liminal distance: right ear, 10 cm.; left ear, 41 cm. Ratio, Left: Right=4.1. Stimulus, Galton whistle, 20,000 vibrations per second.

Set		Heard		Displacement toward axis of stronger ear	Displacement toward axis of weaker ear
Horizontal	Vertical	Horizontal	Vertical		
45° R F	0°	40° R F	0°	5°	
135° L F	0°	110° L F	0°	25°	
0° B	0°	15° L F	10° u	15°	
135° R F	0°	15° R F	20° u	30°	
45° L F	45° u	60° L F	5° u	15°	
180° F	0°	50° L F	25° u	50°	
135° L F	45° u	90° L F	35° u	45°	
45° L F	45° d	55° L F	10° d	10°	
150° R F	0°	120° R F	18° u		30°
0° B	45° u	25° L F	30° u	25°	
45° R F	45° u	25° R F	30° u	20°	
180° F	45° u	35° L F	32° u	35°	
135° R F	45° u	15° R F	35° u	30°	
150° L F	45° u	90° L F	5° u	60°	
0° B	90° u	5° R F	20° u		5°
70° L F	0°	75° L F	0°	5°	
50° R F	45° d	120° R F	15° u		10°
70° R F	0°	30° R F	15° u	40°	

Average displacement toward axis of stronger ear, 18.2°.

as that of the Galton whistle used in the earlier experiments, and care was taken to give the stimulus as nearly as possible the same intensity each time. The stimuli were all given at the level of the ears, and no account of vertical displacements was taken in recording the results, since these have no direct bearing upon the purpose of the experiment.

Tables XIII, XIV, and XV give the results of this investigation. These results, on the average, show that the ratio of sensitivity of the two ears affects the localization of simple tones almost, if not quite, as much as it does the localization of clangs of the degree of complexity of the Galton whistle.

TABLE X

Observer *R*. Showing the influence of the binaural ratio on the localization of clangs. Sensitivity of two ears equated. Left ear plugged. Liminal distance: right ear, 18.5; left ear, 18.2 cm.; Stimulus, Galton whistle, 20,000 vibrations per second.

Set		Heard		Displacement toward axis of right ear	Displacement toward axis of left ear
Horizontal	Vertical	Horizontal	Vertical		
0° B	0°	50° R F	42° d	50°	
180° F	0°	35° R F	30° d	35°	
0° B	45° u	40° R F	30° d	40°	
180° F	45° u	50° R F	8° d	50°	
0° B	45° d	40° R F	25° d	40°	
180° F	45° d	30° R F	25° d	30°	
0° B	90° u	30° R F	42° d	30°	
0° B	0°	35° R F	40° d	35°	
180° F	0°	30° R F	44° d	30°	
0° B	45° u	20° R F	28° d	20°	
180° F	45° u	20° R F	32° d	20°	
0° B	45° d	10° R F	35° d	10°	
180° F	45° d	35° R F	35° d	35°	
0° B	90° u	15° R F	38° d	15°	

Average displacement toward axis of right ear, 31.4°.

TABLE XI

Observer *R*. Showing the influence of the binaural ratio on the localization of clangs. Attempt to correct localizing error. Left ear plugged. Liminal distance: right ear, 19 cm.; left ear, 40 cm. Ratio, Left : Right = 2.1. Stimulus, Galton whistle, 20,000 vibrations per second.

Set		Heard		Displacement toward axis of right ear	Displacement toward axis of left ear
Horizontal	Vertical	Horizontal	Vertical		
0° B	0°	10° R F	28° d	10°	
180° F	0°	20° L F	35° d		20°
0° B	45° u	0° B	32° d	0°	0°
180° F	45° u	10° L F	25° d		10°
0° B	45° d	0° B	35° d	0°	0°
180° F	45° d	5° R F	35° d	5°	
0° B	90° u	5° R F	50° d	5°	
0° B	0°	0° B	32° d	0°	0°
180° F	0°	0° B	20° d	0°	0°
0° B	45° u	10° L F	35° d		10°
180° F	45° u	5° L F	30° d		5°
0° B	45° d	15° R F	32° d	15°	
180° F	45° d	0° B	20° d	0°	
0° B	90° u	10° L F	42° d		10°

Average displacement from median plane, 1.4° (left).

TABLE XII

Observer *R*. Showing the influence of the binaural ratio on the localization of clangs. Artificial sensitivity series. Attempt to correct localizing error. Left ear plugged. Liminal distance: right ear, 19 cm.; left ear, 29 cm. Ratio, Left: Right = 1.5. Stimulus, Galton whistle, 20,000 vibrations per second.

Set		Heard		Displacement toward axis of right ear	Displacement toward axis of left ear
Horizontal	Vertical	Horizontal	Vertical		
0° B	0°	5° R F	30° d	5°	
180° F	0°	5° L F	15° d		5°
0° B	45° u	10° R F	30° d	10°	
180° F	45° u	0° B	30° d	0°	0°
0° B	45° d	0° B	15° d	0°	0°
180° F	45° d	0° B	15° d	0°	0°
0° B	90° u	0° B	40° d	0°	0°
0° B	0°	5° R F	38° d	5°	
180° F	0°	5° L F	22° d		5°
0° B	45° u	15° R F	30° d	15°	
180° F	45° u	0° B	35° d	0°	0°
0° B	45° d	0° B	25° d	0°	0°
180° F	45° d	0° B	25° d	0°	0°
0° B	90° u	5° R F	40° d	5°	

Average displacement from median plane, 2.1° (right).

But the effect is not nearly so consistent in the individual judgments. When the Galton whistle was used as stimulus, the sound was displaced toward the axis on the side of the stronger ear in a very large percentage of cases, and, relatively speaking, in not widely varying amounts. In the case of the tuning fork, however, a very large displacement of the sound toward the axis on the side of the stronger ear was frequently followed by one toward the axis on the side of the weaker ear, the variation in the individual judgments from the true position being, in general, very much greater than for the Galton whistle. It would appear then, in these experiments, that the binaural ratio has exerted its influence both as difference in intensity and as change of timbre.[1] For the sake of comparison,

[1]A few words, further explaining and qualifying the above argument, are probably not out of place here. The tone of the Galton whistle set at 20,000 vibrations is relatively simple. The first overtone, for example, has a vibration rate of 40,000, and the second of 60,000, which is above the limit of audibility. Thus our argument that the above mentioned displacements have been made in terms of the intensity factor should not rest so much, probably, upon a correspondence of results when Galton whistle and tuning fork are used as sources of sound, as upon the fact that the large displacements observed took place both when a simple and a relatively simple tone were used as stimuli. To complete the investigation a comparison should

TABLE XIII

Observer *F*. Showing the influence of the binaural ratio on the localization of simple tones. Liminal distance: right ear, 40 cm.; left ear, 40 cm. Ratio, Right : Left = 1. Stimulus, tuning fork, 480 vibrations per second.

Set	Heard	Displacement toward axis of right ear	Displacement toward axis of left ear
135° L F	70° L F		25°
0° B	0° B	0°	0°
45° L F	60° L F		15°
135° R F	45° L F		90°
60° L F	60° L F	0°	0°
120° L F	120° L F	0°	0°
50° L F	80° L F		30°
180° F	0° B	0°	0°
150° L F	65° L F		35°
0° B	0° B	0°	0°
135° L F	90° R F	135°	
45° R F	45° R F	0°	0°
0° B	125° R F	55°	
60° R F	15° R F		45°
180° F	85° L F		85°
120° R F	60° R F	0°	0°
30° R F	130° R F	20°	
150° R F	135° R F	15°	
0° B	10° R F	10°	
45° R F	90° R F	45°	
180° F	20° L F		20°

Average displacement from median plane, 3.09° (left).

the same observers were used here that were used in the experiments with the Galton whistle. In order to show the effect of the binaural ratio, it was deemed advantageous, in both cases, to work with observers both of equal and of unequal sensitivity of the two ears.

Table XIV shows the results for Observer *R*. The ratio of sensitivity was chosen so that left : right = 2.3; the average displacement toward the axis on the side of the stronger ear was found to be 15°. A correlation of average displacement with ratio of sensitivity shows, roughly speaking, for this observer, quite as much tendency to displace the sound to the side of the stronger ear as was shown for the Galton whistle.

Results with the Galton whistle are brought forward from Tables II, IV, and VI for comparison. Table II shows for *R*.

be made further of the results obtained with these two sources of sound and one still more complex than the Galton whistle. This comparison will be included in the work on this problem still in progress in this laboratory.

a ratio of sensitivity left: right = 4, an average displacement toward left of 20.3°; Table IV, a ratio of sensitivity left: right = 23.6, an average displacement toward the left of 31.6°; Table VI, a ratio of sensitivity right: left = 6.2, and an average displacement of 34.4° toward the right.

Table XV shows the results for Observer *S.*, with a ratio of sensitivity chosen so that right: left = 1.9. With this ratio it was found that the sound was displaced, on the average, 7.5° toward the side of the stronger ear. When compared with a ratio left: right = 2.9 and an average displacement of 10.7° toward the left ear (Table III), a ratio right: left = 9.7 and an average displacement toward the right of 17.2° (Table V), and a ratio left: right = 3.8 with an average displacement toward the left of 34.6° (Table VII), these results also show probably as strong a tendency to displace the simple tone toward the stronger ear as was shown in the case of the clang.

TABLE XIV

Observer *R.* Showing the influence of the binaural ratio on the localization of simple tones. Liminal distance: left ear, 49 cm.; right ear, 21 cm. Ratio, Left : Right = 2.3. Stimulus, tuning fork, 480 vibrations per second.

Set	Heard	displacement toward axis of stronger ear	Displacement toward axis of weaker ear
45° R F	85° R F		4°
135° R F	30° R F	15°	
0° B	40° L F	40°	
60° R F	40° R F	20°	
180° F	0° B	0°	0°
30° R F	55° R F		25°
150° R F	40° L F	70°	
0° B	55° R F		55°
45° R F	55° R F		10°
135° R F	50° L F	95°	
0° B	85° L F	85°	
135° L F	35° L F		10°
0° B	35° R F		35°
45° L F	75° L F	30°	
0° B	50° L F	50°	
120° L F	55° L F		5°
50° L F	55° L F	5°	
180° F	60° L F	60°	
150° L F	40° R F		70°
0° B	45° L F	45°	
135° L F	70° L F	25°	
45° L F	85° L F	40°	

Average displacement toward axis of stronger ear, 15°.

TABLE XV

Observer *S*. Showing the influence of the binaural ratio on the localization of simple tones. Liminal distance: right ear, 86 cm.; left ear, 46 cm. Ratio, Right : Left = 1.9. Stimulus, tuning fork, 480 vibrations per second.

Set	Heard	Displacement toward axis of stronger ear	Displacement toward axis of weaker ear
135° L F	35° R F	80°	
0° B	25° L F		25°
45° L F	35° L F	10°	
0° B	40° L F		40°
60° L F	70° L F		10°
120° L F	40° R F	100°	
50° L F	65° L F		15°
180° F	45° R F	45°	
135° R F	0° B		45°
150° L F	10° L F	20°	
0° B	50° R F	50°	
180° F	10° L F		10°
135° L F	120° R F	105°	
45° L F	75° L F		30°
45° R F	10° R F	25°	
0° B	70° L F		70°
60° R F	75° R F	15°	
0° B	15° L F		15°
180° F	50° R F	50°	
120° R F	45° R F		15°
30° R F	60° R F	30°	
45° R F	45° L F		90°

Average displacement toward axis of stronger ear, 7.5°

C. INDIVIDUAL PREFERENCES

Of the individual preferences reported by von Kries[1] and Dunlap,[2] the writers find this much evidence. There is (1) a

[1]The individual preferences mentioned by von Kries (*Ueber das Erkennen der Schallrichtung*, Ztschr. f. Psychol., I, 1890, s. 242-243) are confined to points in the median plane. The results obtained by us bear more specifically upon the preferences reported by Dunlap.

[2]Dunlap (*The Localization of Sounds*, Psychol. Rev. Monog. Suppl., 1909, Vol. X, No. 40, 1-16) says: "Several years ago I commenced the attempt to make comparisons between the location of sounds with both ears and the location with one ear, the other being stopped as well as might be. The results of my first tests were rather odd, showing a condition which made it impossible to get at the comparisons I wished, at least in any clear way; and subsequent tests which I have made from time to time, and which students have made for me, on different subjects, have resulted in the same way. The condition mentioned has had so little (if any) consideration in connection with the problem of the location of sounds, that I have thought it important to give some account of my experiments." The condition

tendency in case of a stronger ear, to refer the sound in the direction of this ear; and (2) in the case of his observers, and the relatively weak stimulus used, there seemed to be a fairly consistent tendency to prefer the back to the front locations; in fact, some observers never located a sound in front. The former tendency gave certain observers a decided right or left "preference," depending upon their defect; and this, combined with the second tendency, tended to limit the localizations to a single quadrant. That is, the back tendency operating to limit the sound to one hemisphere, and the right or left tendency to a hemisphere at right angles to this, would tend to confine the localizations to one quadrant for a given observer. But these tendencies can hardly be called capricious, as Dunlap apparently found them to be. To show that the one conforms to law, *i. e.*, is correlated with a definite sensory characteristic, has been the object of this paper. The other is still under investigation.[1]

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which discouraged further work on his problem may be summed up in his own words: "The position in the area of location bears precious little relation to the actual position of the sound. The marks representing the sounds at the various points might to all intents and purposes be shaken up in a box and dumped down on the preferred area on the chart. This appearance is amply confirmed by other series on the subjects. Repeated series give results which have no uniformity, except in the general area of location.

"The preferred position is not determined by the character of the sound or by the environment. Two subjects in exactly the same circumstances may have quite different preferences. A subject may show the same preference after six months or a year, or may show a decidedly different one, without any known reason for the change. The subject shows the same preference in different rooms, or if he is reversed in the same room. Alterations in the intensity of the sound produced no definite alterations in the preferred area. The Galton whistle gives practically the same results as the buzzer or the telephone receiver. So far I have not found a subject who does not localize in this preferential way. What the causes are, I cannot say. There are possible theories and nothing more. Meantime, how to conduct profitable experiments in localization before solving this problem is another problem."

The writers admit that the irregularity of Dunlap's results is discouraging. After a careful study of Dunlap's charts of results, they also admit that the factors underlying the evidences of individual preferences of their own observers fail utterly to solve "the puzzle." They can only repeat that in their contention for a lawful mechanism, they do not wish to go beyond the results and conditions of their own experiments; and merely suggest that Dunlap may have worked with the subjective type of observer, and may have fostered this subjective tendency by the use of the chart method for indicating directions.

[1]It has been discussed at various times in the literature of auditory localization whether back reference may not have become associated with weak intensities of sound. (Thompson: *The Pseudophone*, Phil. Mag. (5) VIII, 1879, 385-390; Bloch: *Das binaurale Hören*. Wiesbaden, 1893, pp. 52-6; Pierce: *Op. cit.* 90-1. A reason for this association has been found in the shape of the external ear as a collector of sound (Pierce: *Op. cit.*, p. 90; Bloch: *Op. cit.*, pp. 25-52). But apart from the cause the writers are investigating the fact in the following way. Observers are selected who,

Moreover, no variation that could be called a consistent change occurred in these tendencies after a lapse of some four months. Certainly nothing has come out with regard to the right or left tendency, from time to time, that cannot be roughly correlated with the results of the accompanying sensitivity tests, as will be shown by the results given in the next section of this paper.

However, in contending for a lawful mechanism, and in suggesting an explanation, of what, on the surface, might be considered as capricious, the writer has no desire to go beyond the results and conditions of his own experiments. Each case must be tried out on its own merits.

Table XVI shows the preference for the back locations. This table was compiled from the results of Tables I-XV inclusive and from Table XVII. The number of readings given back and in front of the aural axis, the number of times the sound was localized in the correct hemisphere and the number of times it was displaced to the opposite hemisphere was determined from the tables; and the ratio of the number of backward displacements to the number of forward displacements was computed from these results.

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with the comparatively weak stimulus used in the preceding experiments, show a marked tendency to locate the sound behind. A graded series of stimuli is then provided, ranging from very weak to very strong, and the regular localizing series is given for each stimulus. If, with an increase in the intensity of the stimulus, there is found to be a decrease in the percentage of back references, the intensity of the stimulus may fairly be said to sustain an associative relation to this direction reference. This method of procedure, the writers believe, offers better possibilities of getting results from which conclusions can be drawn than do the experiments of the kind performed by Bloch, even though Bloch's principle of working be carried out under laboratory conditions. Bloch selected a sound of such intensity that when it was given behind, it was localized behind by his observers; and then he tried the effect of an increase of intensity. He claimed thus to be able to cause a reversal of the localization, or the illusion of front. Bloch's method of experimenting was extremely crude. The experiments were made in the open air in a court enclosed on three sides. "The observer stood 5 meters from the end wall and pebbles were thrown on the stone pavement in front or behind him. The result was that when his face was turned towards the wall, the legitimate influence of the pinna was merely increased and the localizations were mostly correct. When, on the contrary, the back was turned towards the wall, sounds coming from behind were apt to be falsely located in front, since now the reflection of the sound waves by the wall produced an unwonted intensity in the sound." Applying this principle of working under laboratory conditions in various ways, the writers have always failed to get anything like consistent results. Any attempt to confirm the association of the back or front reference with the intensity of the sound, based upon individual judgments, they believe is doomed to failure. If conclusions are to be reached at all they must be reached from a comparison of averages got by a systematic variation of intensity.

TABLE XVI

Showing, with the comparatively weak stimulus used, the preference of our observers for back locations.

Tables from which data are taken	No. of readings given back of aural axis	No. localized in correct hemisphere	No. displaced in front of aural axis	No. of readings given in front of aural axis	No. localized in correct hemisphere	No. displaced back of aural axis	Ratio of displacement back to displacement front
Table I	11	10	1	8	3	5	5 : 1
Table II	10	10	0	8	0	8	8 : 0
Table III	12	12	0	8	0	8	8 : 0
Table IV	10	10	0	8	0	8	8 : 0
Table V	10	10	0	9	0	9	9 : 0
Table VI	10	10	0	9	0	9	9 : 0
Table VII	10	10	0	8	0	8	8 : 0
Table VIII	9	9	0	9	2	7	7 : 0
Table IX	10	9	1	8	4	4	4 : 1
Table X	8	8	0	6	0	6	6 : 0
Table XI	8	8	0	6	0	6	6 : 0
Table XII	8	8	0	6	0	6	6 : 0
Table XIII	11	9	2	10	3	7	7 : 2
Table XIV	13	13	0	9	0	9	9 : 0
Table XV	13	13	0	9	1	8	8 : 0
Table XVII	9	9	0	8	0	8	8 : 0

D. THE QUESTION OF CHANGES IN THESE PREFERENCES WITH LAPSE OF TIME

Experiments were conducted to find out whether any considerable change occurred in the observer's tendency to localize during the course of several months, or, more especially, to determine whether there occurred any change that could not be correlated with a corresponding change in the ratio of sensitivity of the ears. No change of any significance was found to have taken place in any of the cases examined. Table XVII shows the results obtained for observer *R.* three months later than those given in Table II. These results may be taken as representative. In Table II, the ratio left:right = 4, and the displacement is 20.3° toward the left; and in the table given below, the ratio left:right = 3.7, and the displacement is 23.3°. This comparison shows a slight increase in the observer's tendency to refer the sound to the side of the stronger ear, but in a field where the results show such a large mean variation the writers have not con-

sidered, either here or elsewhere in the work, that so small a change in results is at all significant.

By comparing the results of Table XVII with Tables II, VI, VII, X, XI, XII, and XIV, in Table XVI, it will be found also that no significant change has occurred in the observer's preference for the back locations.

TABLE XVII

Observer *R*. Showing that no change of any consequence has taken place in the localizing tendency of our observers after a lapse of three months. (Compare with Table II.) Liminal distance: right ear, 19 cm.; left ear, 71 cm. Ratio, Left : Right = 3.7. Stimulus, Galton whistle, 20,000 vibrations per second.

Set	Heard	Displacement toward axis of stronger ear	Displacement toward axis of weaker ear
0° B	25° L F	25°	
180° F	50° L F	50°	
45° L F	65° L F	20°	
130° L F	65° L F	15°	
70° L F	70° L F	0°	0°
135° L F	80° L F	35°	
0° B	15° L F	15°	
135° R F	15° R F	30°	
45° R F	25° R F	20°	
150° R F	20° R F	10°	
60° L F	75° L F	15°	
135° R F	10° R F	35°	
60° R F	10° R F	50°	
50° L F	60° L F	10°	
130° R F	25° R F	25°	
180° F	20° L F	20°	
0° B	20° L F	20°	

Average displacement toward axis of stronger ear, 23.2°.

III. SUMMARY OF RESULTS.

(1) Subjects having a natural difference in the sensitivity of the two ears show a constant tendency to displace the sound toward the axis on the side of the stronger ear; and, conversely, subjects without this difference in sensitivity do not show this tendency. The greater number of subjects examined showed a difference in sensitivity.

(2) Changes in the ratio of sensitivity, produced by plugging either ear, were followed by corresponding displacements of the sound toward the axis on the side of the stronger ear. Differences in sensitivity, artificially produced, apparently

exerted a greater influence upon localization than did approximately equal differences due to natural defect. This is probably because, in the case of a natural defect, the localization error has been partly corrected, in the past experience of the subject, through association with the direction reference of other sense-organs.

(3) In the case of observers who showed a characteristic right or left tendency, it was found possible to change the ratio of sensitivity so that the error in localization was corrected. This result was not accomplished by equating the sensitivity of the two ears. The desired ratio was always found to have a value somewhere between equal sensitivity and the old ratio.

(4) The average results showed that changes in the binaural ratio affected the localization of simple tones almost, if not quite, as much as it did the localization of clangs of the degree of complexity of the Galton whistle. The individual judgments, however, showed a much larger variation from the true position in the case of the simple tones. It would appear, then, that in these experiments the binaural ratio exerted its influence both as difference in intensity and as change of timbre, but predominantly as difference in intensity.

(5) The writers find this much evidence of individual preferences in localization (von Kries', Dunlap). (*a*) There is a tendency in case of a stronger ear to refer the sound in the direction of that ear. This gave certain observers a decided right or left tendency, depending upon the kind and amount of their defect. (*b*) With the relatively weak stimulus used, there seemed to be a fairly constant tendency for the observers to prefer back to front locations. But these tendencies cannot in any sense be called capricious. One is directly traceable to the binaural ratio; the other is still under investigation, and is probably an effect of the intensity of the stimulus used.

(6) No changes of any consequence in these tendencies were found during the course of several months, as occurred in the case of Dunlap's observers,—certainly none that could not be correlated with a definite change in the localizing clue. For example, a cold, or what not, was sometimes found to produce a change in the observer's right or left tendency, but tests of the sensitivity of the two ears always disclosed a corresponding change in the binaural ratio.

In this study, nothing was undertaken bearing upon the later aspects of the intensity theory brought out by the papers of Rayleigh[1] and Wilson and Myers.[2] The writers, however,

[1]Rayleigh: *On our Perception of Sound Direction*, Philos. Mag. (6), XIII, 1907, pp. 214-32.

[2]*Op. cit.*

have begun experiments upon three points relative to these aspects. (1) It will be determined whether tones of 128 vibrations or less per second have a larger j. n. d. of direction than tones of higher pitch. This the intensity theory would seem to require, according to Rayleigh's calculations of the relative intensity of the waves received by the two ears. Rayleigh's tests of this point were as rough as possible. They consisted, it will be remembered, in determining whether stimuli of both low and high pitch, given in the region of the aural axis, could be judged as right or left without mistake. Now, working under these conditions, a considerable difference in direction-sensitivity might obtain for the two kinds of tones, and still no mistake be made in either case. The positions chosen give the largest possible binaural ratio, and the judgments required are the most general that could possibly be made. In short, a less sensitive method for detecting small differences in power to discriminate direction could hardly have been devised. The size of the j. n. d. is obviously the proper criterion to apply. (2) The series of experiments used in this paper will be repeated, using forks of low and high frequency. If there is found as much tendency to displace the tones of low pitch as those of high pitch, the results should argue that the localizing clue for low tones is the binaural ratio, instead of the power directly to detect phase differences; because (a) the change in the sensitivity of the ear does not affect the phase of the sound wave, and (b) it could not affect the detection of the phase differences by the ear in such a manner as to displace the sound toward the stronger ear, for by this hypothesis, ratio of effect has nothing to do with localization. At least, it cannot be assumed that the binaural ratio, which is computed in terms of intensive difference, could be translated directly into terms of recognition of phase difference. Apparently the only effect that could follow a decrease of sensitivity of one ear would be a proportionate confusion and uncertainty of localization, not a definite and characteristic displacement toward the axis on the side of the stronger ear. (3) The settings given to the stimuli in Wilson and Myers's experiments will be repeated under ordinary localizing conditions, in order to see whether the transfer of the sound from one side of the median plane to the other takes place when the direct paths of transmission to the two ears are changed by the amounts they used. If the transfers do not take place, some evidence, at least, will be afforded that the experiments they describe and the conclusions they reach do not bear directly upon the phenomenon of localization as it ordinarily occurs, but only upon a special

phenomenon created by their conditions, which favored bone conduction.

The writers present this report with the hope that their results establish a more definite correlation between the binaural ratio and direction-reference than has previously been attained, and that the experiments described will provide an easily available means of clearly demonstrating this correlation in the teaching laboratory.